feedback

OPERATION BREAKTHROUGH

U.S. Department of Housing and Urban Development

A COMPENDIUM OF THE PERFORMANCE TESTING PROGRAM

6

VOLUME

foreword

The Department of Housing and Urban Development (HUD) initiated Operation BREAKTHROUGH in May 1969 to demonstrate the feasibility of large scale factory production of quality housing for all income groups using new materials and industrialized methods. An important feature of the program was the introduction of the performance approach in place of the then customary prescriptive and descriptive specification approach. This performance approach was set forth in a series of Guide Criteria which were used as the basis for the design and evaluation of the housing systems.

This compendium is intended to be a generalized recap of the performance testing undertaken to evaluate the BREAKTHROUGH housing systems. Testing was required because of the innovations introduced into the housing systems and their construction process, which, due to their unusual nature, could not be evaluated by comparison or analysis; consequently, it was only by means of physical testing that compliance with the performance recommendations could be determined.

We hope that this compilation of test methods and summary of results will prove useful to architects, engineers, designers, builders, building officials, and others interested in the performance concept. The compendium is provided as a source of information only to improve the state of the art and the description of a test in this report does not imply an endorsement by HUD of any building material, component, assembly or method.

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introduction

1.1 PERFORMANCE CONCEPT OF DESIGN

One of the important technical features of Operation BREAKTHROUGH was the introduction, for the first time and on an organized, full scale basis, of the performance criteria concept. Design specifications and building regulations in the United States typically establish, on a prescriptive basis, requirements usually stated in terms of known materials and methods of use. Requirements established in the regulations are based on long experience rather than in terms of results to be obtained.

The Operation BREAKTHROUGH Guide Criteria [1] [1], on the other hand, were written to express building requirements in terms of end performance results determined from user needs. Thus, instead of suggesting that the span-depth ratio of a floor system should not exceed a certain value, it would be stated that deflections should not cause discomfort or inconvenience to occupants or damage to building elements. Further recommendations that live load and long term deflections be less than a certain percentage of the span would then be added on the basis of experience to represent reasonable limits of human perception or material strains.

The performance concept, in the course of opening the way for new materials and methods, or new uses of old materials, may require a substantial amount of physical testing. For example, deflections of well known materials can generally be determined analytically with sufficient accuracy, but those of a sandwich panel consisting of synthetic surfaces bonded to a paper honeycomb core are a different matter. Not only will the properties of the individual materials (including the long term behavior of the laminating adhesive) have to be determined, but also the load carrying characteristics of the entire assembly. To the greatest extent possible, and within the constraints of the state of the art of the performance concept, performance statements call for procedures such as physical simulation, model study, full scale testing, etc. as aids in evaluation.

1.2 DEVELOPMENT OF THE GUIDE CRITERIA

Early in the program general guidelines were established by HUD in consultation with NBS,[2] to set the intent of criteria for evaluation of housing systems proposed for use in BREAKTHROUGH. Their three basic features were:

1. The principles of established building codes, particularly their intent, would be followed as closely as possible. Public health and safety protection provided by present codes would be maintained as a minimum.
2. Criteria consistent with those principles would be developed to cover matters not treated in the codes.
3. Provisions would be based on performance, to the greatest extent possible, without prescribing specific materials.

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[1] Numbers in brackets indicate references listed in section 5.

[2] National Bureau of Standards, U. S. Department of Commerce

The BREAKTHROUGH Guide Criteria were developed on the basis of these guidelines. For each property to be investigated there is a general statement of the recommendations for that property followed by specific criteria for each recommendation and methods for evaluating each criterion. The levels of performance set for each criterion were generally based on accepted practice; where current knowledge was inadequate, exploratory testing was performed on conventional housing systems to establish levels consistent with this basis.

1.3 OPERATION BREAKTHROUGH TESTING

Testing performed in the course of Operation BREAKTHROUGH was done primarily for:

1. Establishment of a particular criterion.
2. Determination of the properties of innovative materials.
3. Measuring the performance of sub-systems or systems.
4. Evaluating the behavior of completed dwelling units.
5. Determining compliance with a criterion.

Whenever possible, established test methods, such as those promulgated by the American Society for Testing and Materials (ASTM), were used. When standard test methods were not available, special test methods were devised to simulate extreme and service conditions from which performance data could be derived.

The Guide Criteria were divided into nine parts on the basis of physical attributes:

1. Structural Serviceability.
2. Structural Safety.
3. Health and Safety.
4. Fire Safety.
5. Acoustical Environment.
6. Illuminated Environment.
7. Atmospheric Environment.
8. Durability—Time Reliability (Function).
9. Spatial Characterics and Arrangement.

Testing most often was performed in connection with criteria dealing with Parts 1, 2, 4, 5, and 8. Evaluation for compliance with criteria in the other parts was ordinarily made from analyses of plans, specifications, and available data.

There were also 12 "built element" divisions as follows:

A. Structure.

B. Walls and Doors, Inter-Dwelling (Interior Space Dividers).

C. Walls and Doors, Intra-Dwelling (Interior Space Dividers).

D. Floor-Ceiling (Interior Space Dividers).

E. Walls, Doors, and Windows (Exterior Envelope).

F. Roof-Ceiling, Ground Floor (Exterior Envelope).

G. Fixtures and Hardware.

H. Plumbing.

I. Mechanical Equipment, Appliances.

J. Power, Electrical Distribution, Communications.

K. Lighting Elements.

L. Enclosed Spaces.

The various criteria were then organized in a matrix form which is shown in fig. 1. The recommendation covering any attribute of any built element can be found at the appropriate intersection of the matrix, which is entered with the letter identifying the built element. Thus, to determine what performance is recommended with respect to air infiltration through outside walls, it is necessary to look at the intercept of E, "Exterior Envelope; Walls, Doors and Windows" with 7, "Atmospheric Environment," and the appropriate criterion will be found in the text of the book at "E.7," were it is given under "E.7.3."

Testing done in connection with Operation BREAKTHROUGH can be divided into three general categories with respect to the Guide Criteria:

1. Fire Safety.
2. Structural Behavior.
3. Miscellaneous (including plumbing, electrical, acoustical, etc.)

By far the largest number of tests (about 120) were in the first category. They have been described in detail in a previous compendium [2], and therefore are discussed only briefly in section 2 of this publication. The approximately 70 tests dealing with structural behavior were generally the most elaborate and original in the BREAKTHROUGH program. About 30 tests dealing with other considerations have been consolidated in the miscellaneous section of this report. The nature of the innovative structures and the properties requiring investigation were such that, in most cases, structural test procedures had to be devised specifically for each feature investigated. On the other hand, testing for fire properties was done largely by established methods, although a certain amount of non-standard testing was required to evaluate the fire safety of a few highly innovative designs.

Tests were made only when it was felt that there was a question as to the ability of proposed materials and systems to comply with Guide Criteria recommendations. Testing was not required when previously available data were considered adequate.

The tests that were performed served an important function in the evaluation process since they filled major gaps in the knowledge of innovative materials and assemblies, and provided data without which it would have been impossible to compare HSP[1] technical submissions with Guide Criteria recommendations.

1.4 THE EVALUATION PROGRAM

Actual work in the design and development phase of the program (Phase 1) commenced with the submission of a conceptual design. This was followed by 25 percent complete plans, specifications, and calculations that were reviewed for compliance with the Guide Criteria. Later submissions and reviews were made at the 95 percent and 100 percent complete stages. Construction under Phase 2 of the program was authorized following acceptance of the 100 percent submission.

[1] Housing System Producer, a term used to define one of the twenty-two firms competitively selected to participate in Operation BREAKTHROUGH

Built Elements			Attributes								
			Structural Serviceability	Structural Safety	Health and Safety	Fire Safety	Acoustic Environment	Illuminated Environment	Atmospheric Environment	Durability/Time Reliability (Function)	Spatial Characteristics and Arrangement
			1	2	3	4	5	6	7	8	9
	Structure	A									
Interior Space Dividers	Walls and Doors, Inter-Dwelling	B									
	Walls and Doors, Intra-Dwelling	C									
	Floor-Ceiling	D									
Exterior Envelope	Walls, Doors and Windows	E									
	Roof-Ceiling, Ground Floor	F									
	Fixtures and Hardware	G									
	Plumbing	H									
	Mechanical Equipment, Appliances	I									
	Power, Electrical Distribution, Communications	J									
	Lighting Elements	K									
	Enclosed Spaces	L									

FIGURE 1
GUIDE CRITERIA MATRIX

Housing System Producer: ____________

Building Type: Single Family Detached (Guide Criteria Vol. IV)

Intercept: A.2 (Continued)

SUMMARY FORM FOR TESTING AND ANALYSIS PROGRAM

Legend

Ma -Material
C -Component
M -Module
H -Housing Unit
HS -Housing System
◯ -Completed (symbol circled)

Criteria Number	Subject	Category I: Evaluation of Plans & Specs. & Documentation — Review of Plans/Specs.	Category I — Computations/Analysis	Category I — Test Data/Industry Cert.	Category II: Evaluation of Physical Elements — Examination	Category II — Testing to be Done	Remarks
A.2.3.1	Structure/Sustained loading (1.2D+1.5L) for 24 hours						
(a)1	dv						
2	dh						
(b)1	dvr						
2	Dvr						
A.2.5.1	Structure/Effect of differential foundation settlement on load capacity						
A.2.6.1	Structure/Capacity of inserts and hangers						
(a)	Ceilings						
(b)	Structural members						
A.2.7.1	Capacity reduction by cutting for utilities						

FIGURE 2
PAGE FROM TESTING AND ANALYSIS (T & A) BOOK

Evaluation of each system was summarized on Testing and Analysis Forms. Each criterion was listed and there was a space for the evaluator to indicate that the system did or did not meet the criteria or could not be judged on the basis of the data submitted. There was also a space for remarks such as "testing was necessary to investigate criterion compliance." A sample page from a T & A report is shown in figure 2. [3]

Evaluation of HSP submissions was made in accordance with the performance recommendations of the Guide Criteria rather than the requirements of local prototype site building codes. However, the Criteria were intended to establish equivalent performance levels in public health and safety matters covered by the codes. Where code provisions were considered inadequate for assessment of innovative designs, recommendations were presented that may not have been considered previously. An example of this was the recommendation that large concrete panel structures be designed to resist progressive collapse so that loss of certain specified members in the building would not lead to failure of the entire structure.

In many cases a review of calculations provided the basis for acceptability. In others, where mathematical analysis could not be accomplished because of a lack of detailed knowledge, test data were required.

2

fire tests

2.1 FIRE SAFETY EVALUATION

The fire safety portions of the Guide Criteria incorporated recommendations comparable to those of building codes including:

1. *Fire Containment:* Limitation of a fire and its effects to the room of origin by means of construction features.
2. *Life Safety:* Protection of occupants and, as required, their safe evacuation.
3. *Early Detection and Suppression*

2.2 SCOPE OF FIRE TESTING

Many different types of fire tests were performed during the BREAKTHROUGH program. Fire endurance tests were performed on wall, ceiling, and floor assemblies to determine their ability to contain a fire. In accordance with the ASTM E 119 [4] test method, they were required to:

1. Support their design loads.
2. Resist the passage of flame, smoke, and heated gases.
3. Limit the temperature rise on the unexposed side of the test specimen.

Structural columns had to support their design loads while exposed to fire. Other fire tests were conducted to study:

1. Passage of fire between floors through a mechanical/electrical core installed in a tall building. (See fig. 3.)

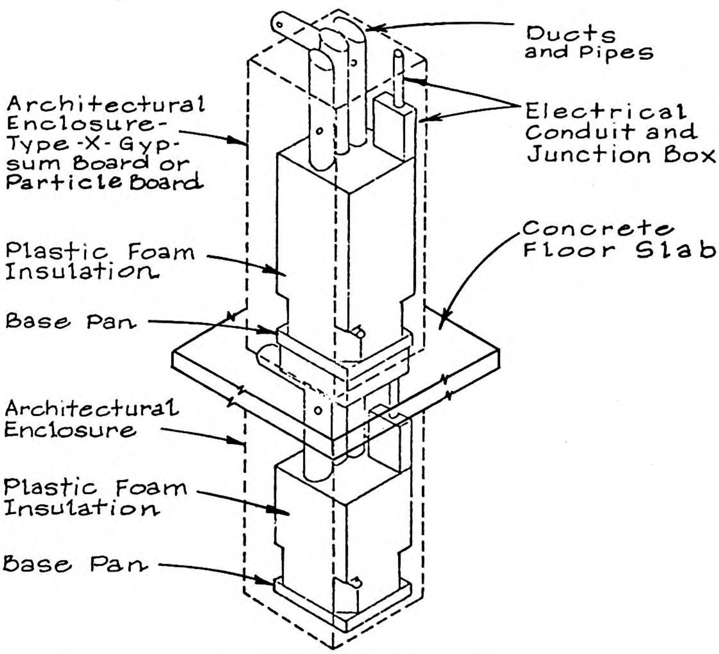

FIGURE 3
MECHANICAL/ELECTRICAL CORE

2. Effects of intumescent coatings on the fire resistance of structural elements.

3. Effects of fire exposure on both sides of a wall instead of on one side only, as is standard practice for fire testing.

Small scale tests were used to study the fire resistance of several floor and roof systems, and this in many cases made it unnecessary to perform more expensive and time consuming large scale tests.

Much of the BREAKTHROUGH fire testing was concerned with the properties of individual materials rather than of built up assemblies. Several different types of flame spread tests were made on wall and ceiling finishes, floor coverings, and kitchen cabinets. Similarly, the smoke generating properties of these materials were measured to ensure that smoke produced from them during a fire would not seriously reduce visibility and thus make it difficult for occupants to escape.

Several other tests were made relating to specific systems or general fire protection concepts. The resistance to ignition by burning embers of a fiberglass reinforced polyester resin roofing system was measured by ASTM Method E 108. [5] The amount of heat that would be released by combustible exterior siding and its flammability were determined by a series of tests that measured potential heat, rate of heat release, and ease of ignition. The effectiveness of a pressurization system for keeping smoke out of an exit stairwell during a fire was tested in an actual building. In this test, sulfur hexafluoride (SF_6) tracer gas was introduced into simulated "burn rooms" on two floors of a twelve story apartment building and the concentration of the tracer gas was measured at different levels in the stairwell during operation of the pressurization system. The spread of fire from a burning room through a window to a nearby wall perpendicular to the window was also studied. This evaluative test included a test mockup of a typical reentrant corner. Layouts having reentrant corners, while common in attached dwellings, are not normally a hazard unless the exterior walls are made of combustible materials or have adjacent window or door openings. (See fig. 4)

2.3 FIRE ENDURANCE TESTING

This testing was primarily conducted in accordance with ASTM Method E 119. Test specimens were mounted in a furnace whose temperature was controlled in accordance with the standard time-temperature curve until failure occurred or until the desired fire endurance time without failure was attained. Walls, floors, ceilings, and structural columns were evaluated by the criteria given in the test method.

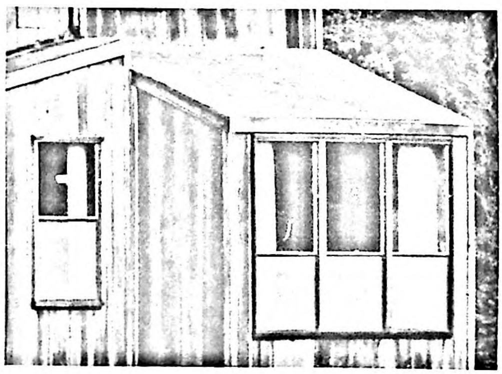

FIGURE 4
MODULAR HOUSING UNIT
ILLUSTRATING A REENTRANT CORNER

Several special conditions were introduced in wall fire endurance tests:

1. The loading frame was divided into two segments of equal length that were individually loaded. This prevented end members from carrying larger than normal loads, thus concealing failure in the central portions of the wall specimen. (See fig. 5.)

2. Load bearing double walls were loaded independently, as would be the case in an actual housing construction with two modules placed side by side. (See fig. 5.)

3. Actual service loads, rather than "theoretical working stresses contemplated by the design," [4] were used in evaluation of fire resistance.

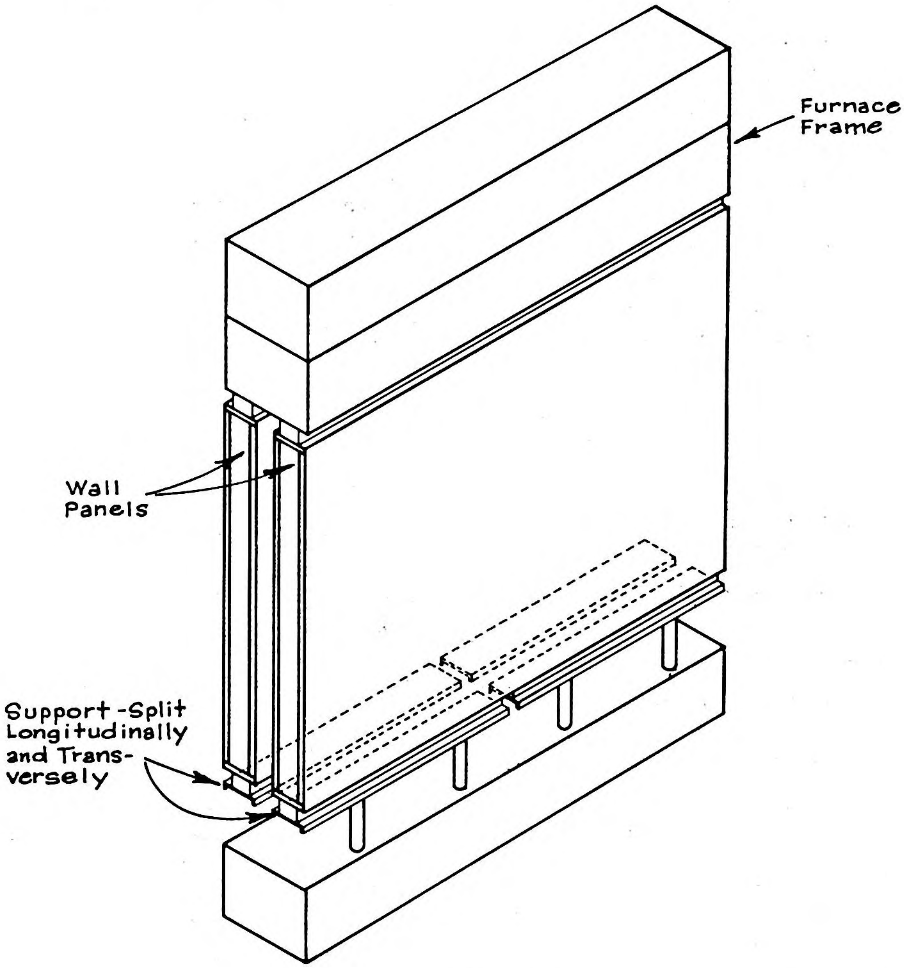

FIGURE 5
SPLIT LOADING FRAME FOR MAKING FIRE ENDURANCE TEST ON WALL PANELS

4. Test loads were applied eccentrically when this situation was found in actual use.

5. Tests conducted at NBS were performed with positive pressure in the upper two thirds of the test furnace to force flame, gas, and smoke through openings that occurred in the wall test assembly.

6. The hose stream test of ASTM Method E 119 was not required, since the emphasis in the BREAK-THROUGH program was on life safety rather than damage from fire and fire fighting.

A wide variety of wall assemblies was evaluated—exterior walls and interior partitions, load bearing and non-load bearing, single interior partitions, and double interior walls representative of the juncture of two modules. Typical assemblies tested included:

1. Corrugated aluminum siding on one side of aluminum studs with gypsum board on the other.

2. Gypsum board on both sides of steel studs.

3. Precast plaster on both sides of steel studs.

4. Two flat sheets of fiberglass reinforced polyester separated by a corrugated sheet of the same material.

5. Steel facing on both sides of a paper honeycomb core.

6. Gypsum board and resin impregnated glass fiber mat on both sides of a paper honeycomb core.

Several floor, floor/ceiling, and roof/ceiling assemblies with innovative features similar to those mentioned above for walls were also studied. Variations from normal testing procedures included the use of carpet and underlayment as a part of floor specimens to simulate more closely actual service conditions, and the small scale tests mentioned previously.

2.4 FLAME SPREAD TESTING

In addition to the requirements for fire endurance, most building codes have limits for flame spread properties of finish materials used in multifamily buildings. These flame spread ratings are generally based on use, with the most severe requirements for furnace rooms and exit corridors and the least for normal living areas such as living rooms and bedrooms, with those for kitchens falling in between. Three categories of materials were evaluated:

1. Wall and ceiling coverings

2. Kitchen cabinets

3. Floor coverings

Because of time and equipment limitations most of the surface flammability (flame spread) tests were conducted using the ASTM E 162 (radiant panel) test [6] rather than the ASTM E 84 (tunnel) test [7] recommended by the Guide Criteria. This allowed the use of small specimens, which were frequently all that were available, and permitted the evaluation of kitchen cabinets whose small size would have made testing by ASTM E 84 difficult. The two methods give comparable results for most materials, and some building codes use them interchangeably. An additional procedure, the so-called "pill test," a Department of

Commerce standard for rating the flammability of carpeting when a hot object (such as a burning cigarette) is dropped on it, was also used to evaluate the fire safety of carpeting. [8], [9]

The major innovation in the BREAKTHROUGH flame spread testing was the use of both carpet and underlayment in the test specimen. Although this is not required by the ASTM test procedure, it was done because the underlayment was found to have a significant effect on the results of small scale fire endurance tests conducted on carpeted floors.

2.5 SMOKE GENERATION TESTING

Smoke generated by burning building materials has been given only indirect, if any, treatment in most building codes, but the increasing use of new synthetic materials has made this a factor of considerable importance. Some of these materials, under even minor fire exposure, can produce great quantities of irritating smoke that can fill rooms and corridors rapidly and reduce visibility to such an extent that escape can be difficult, if not impossible. For this reason, the Guide Criteria recommended limits for smoke generation.

Testing was principally conducted in the NBS Smoke Density Chamber in which the amount of smoke generated by a test specimen exposed to a radiant heat source is determined by the photometric measurement of the attenuation of a light beam. In those few cases where ASTM E 84 was used to determine flame spread, smoke generation was measured as an integral part of the E 84 test.

3

structural tests

3.1 CLASSIFICATION OF TESTS

Tests involving structural behavior have been divided as follows:

1. Exploratory tests not pertaining to any particular BREAKTHROUGH housing system but which were made to develop information from which a criterion could be derived or by which it could be justified.
2. Tests related to specific Operation BREAKTHROUGH systems intended to study:
   a. Properties of materials.
   b. Construction details.
   c. Assemblies.
   d. Large units.

3.2 EXPLORATORY TESTING

3.2.1 FULL SCALE TESTS ON A TWO STORY HOUSE SUBJECT TO LATERAL LOADS [10]

When the BREAKTHROUGH Program was initiated, there was not sufficient information available about the drift (lateral movement) of low buildings to permit recommendations of allowable values. Specification limits had been set for tall buildings of normal types of construction, usually given as a fraction of the height. However, it was not known if these limits could be applied properly to low residential structures. This test series was conducted to determine the applicability of these drift limits. Lateral load studies were made on a conventional house representative of those built in various parts of the country by one of

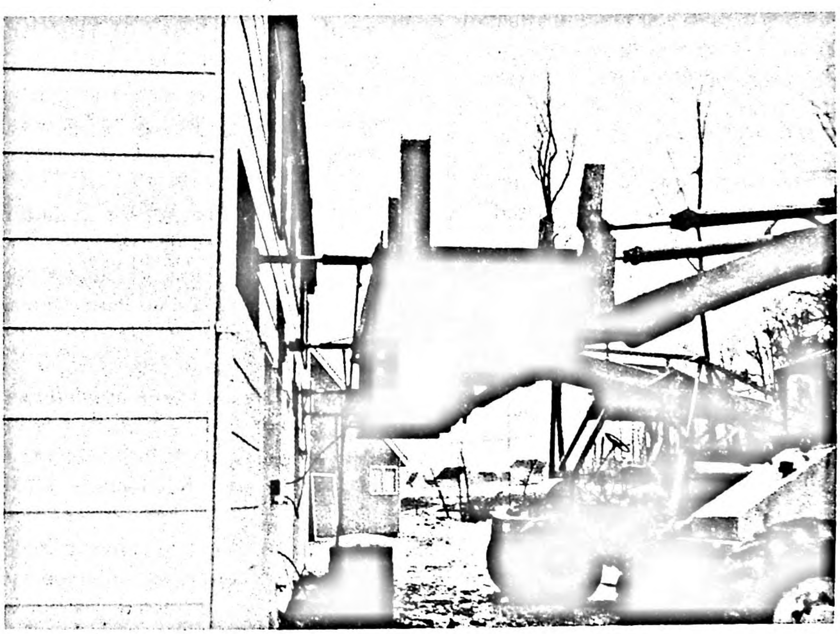

FIGURE 6
APPLYING LATERAL LOADS TO FULL SCALE TWO STORY HOUSE

the HSPs. There were distinct tests to measure drift under a simulated wind load and dynamic response under an impulse load.

The test house was a two story, basementless, single family dwelling in a typical suburban residential development. Loads were applied by hydraulic jacks pushing against the house at four points and reacting against two fork lift trucks weighted with large concrete blocks. (See fig. 6.) An impulse load was obtained by sudden removal of one of the forces. Static (simulated wind) loads were applied at both the second floor and roof levels and displacements measured with electronic devices.

Measurements were made of upper and lower story lateral displacements. Natural frequency and damping were determined for the impulse load and observations made during the static load test of the distortion of floor/ceiling diaphragms and the effect of interior finishes on the racking resistance of the interior walls.

Test results showed that:

1. Measured drift was considerably smaller than would be computed by application of the design criteria generally used for tall buildings.
2. Let-in bracing resisted a major portion of the racking load on the exterior walls (with only a small part carried by the gypsum wallboard).
3. The second floor acted as a rigid diaphragm while the second story ceiling was subjected to considerable deformation.

Experimental results indicated that the limits recommended by the Guide Criteria and derived from those commonly used for tall structures are reasonable and applicable to low rise housing.

3.2.2 THE EFFECT OF IMPACT LOADING ON THE PERFORMANCE OF WOOD JOIST SUBFLOORING SYSTEMS [11]

Prior to Operation BREAKTHROUGH there was no reliable guide to the performance that could be expected of flooring systems. Because of the widespread use of wood joist floors it was felt that the impact resistance of this type of construction would provide a good basis for criterion recommendations, but sufficient data were not available. This investigation was made to obtain data to establish limits relative to impact resistance. While it is neither directly related to any specific Operation BREAKTHROUGH system nor to any provision in the Guide Criteria, it is partly concerned with criteria dealing with "Floor-Ceiling Serviceability" summarized as follows in the commentary:

> "Criterion (a) intends to determine whether the floor will withstand occasional impact loads resulting from occupancy (a man falling from a ladder) without suffering structural damage. Criterion (b) deals with concentrated loads applied to the surface of the structural floor by certain items of furniture and by other occupancy loads."

Testing was done on "conventionally constructed" floors with plywood surfaces, and should be considered as a study of the plywood decking since the supporting joists rested on the laboratory floor. Test procedures varied somewhat, but most tests

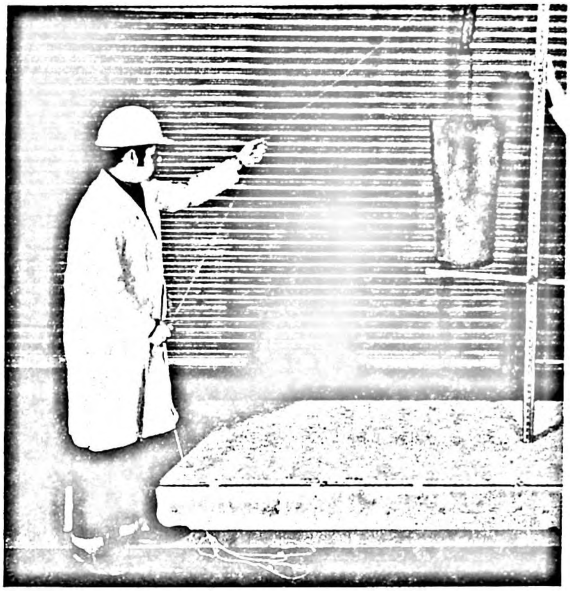

FIGURE 7
APPARATUS FOR APPLYING IMPACT LOADS TO WOOD JOIST FLOORS

consisted of impact loads (see fig. 7) of increasing magnitude alternating with static loads of a fixed magnitude being applied to the test specimens. Deflection measurements indicated that the deflection caused by a given concentrated load increases as the impact energy previously applied to the floor increases.

If the maximum impact load likely to be encountered in a dwelling is known, the results of this test provide a means of making a practical choice of subflooring to restrict deflections to a specified value.

3.2.3 STUDY OF THE LOCAL RESISTANCE OF CONVENTIONAL PLYWOOD SUBFLOORING TO CONCENTRATED LOADS [12]

Another feature of the behavior of housing floor systems for which there had not been a good guide was their resistance to concentrated loads. Floors have generally been required to support a distributed load plus, in the case of office buildings, a concentrated load representing a safe or other heavy piece of furniture. However, nothing has been said about extreme concentrated residential loads such as a piano resting on small casters. This problem was considered in the Guide Criteria, and the tests described in this subsection were conducted to compare the performance of conventionally constructed plywood floors with the following recommendations:

> The structural floor should resist a 400 lb load, applied on a circular area of 5/8 inch diameter and sustained for one hour without causing a residual indentation of the structural surface in excess of 1/16 inch measured one hour after removal of the load, and a 280 lb long term sustained load applied on a circular area of 5/8 inch diameter.

If the wearing surface is of nondurable material, or if there is a possibility that this surface may be removed during the useful life of the structure, the floor should satisfy the criterion with the wearing surface removed.

These recommendations are particularly significant in the case of floors constructed of sandwich panels with thin skins. In order to minimize problems with the thin skins, plywood "walking surfaces" were incorporated in those BREAKTHROUGH designs that used this type of panel.

Seven floor systems with various combinations of plywood and hardboard were evaluated. These were supported by shallow "joists" spaced from 6 to 24 inches on center, although most were on conventional 16 inch centers. Since these members were supported continuously on the laboratory floor, the test results were primarily concerned with properties of the flooring surface and did not take into account the possible effects of joist deflection. (See fig. 8.)

Loads were applied at several locations in each panel, including over the joists and at free edges. Testing techniques differed from ASTM E 72 [13] for the structural strength of a system and ASTM D 2394 [14] for finished flooring, since it was felt that these were not applicable to floor systems with thin skins. Loaded area diameters of one inch, 5/8 inch, and in a few cases, 1/2 inch were used. Most load applications were taken directly to failure although in some cases loads were removed and reapplied with an increased magnitude.

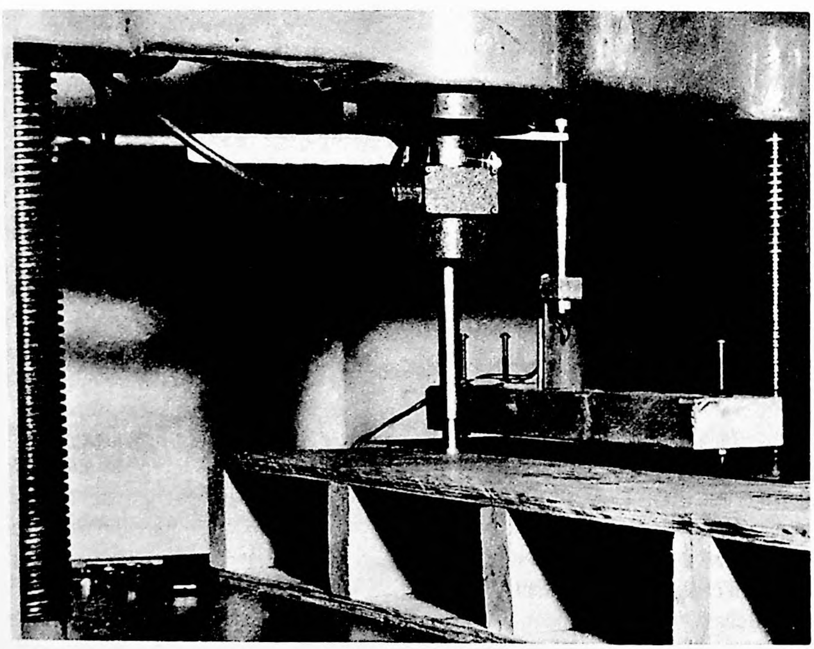

FIGURE 8
TEST SET UP FOR APPLYING CONCENTRATED LOADS TO PLYWOOD SUBFLOORING

All failure loads exceeded the Criteria recommendations. This test, although not directly related to any specific Operation BREAKTHROUGH system, showed the applicability of the Criteria relative to the strength of floor systems under concentrated loads, and is of particular importance in connection with innovative construction methods without a long history of generally satisfactory service.

3.2.4 TRANSIENT VIBRATION TESTS ON WOOD JOIST FLOORS [15]

Very little experimental work has been done to investigate the subject of transient vibration and its effects on human comfort. The Guide Criteria included some provisions on this subject, but it was not known how these compared with the behavior of conventionally constructed, generally satisfactory, floor systems. This test was made to compare the transient vibration characteristics of such systems with the recommendations of the criterion that indicated:

> "Transient vibrations induced by human activities should decay to 0.2 of their initial displacement-amplitude within a time not to exceed 1/2 second."

Testing was carried out in a total of 34 rooms in seven completed prototype dwelling units—four furnished and three unfurnished. A load was applied by dropping a bag weighing 25 lb from a height of 3 ft. This was intended to approximate the energy delivered by a person weighing 150 lb walking rapidly across the floor. Electronic measuring devices supported on beams mounted on the walls were used to read floor deflections (See fig. 9.) Four different arrangements of gages and impact locations were used viz:

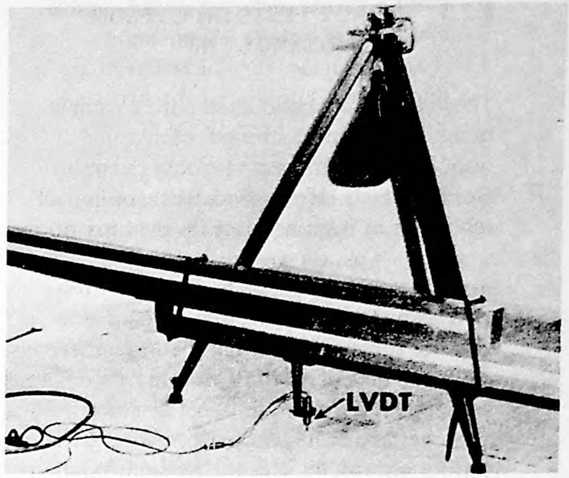

FIGURE 9
APPARATUS FOR
INDUCING TRANSIENT VIBRATIONS

1. Gage over joist; weight falling between joists.
2. Gage over joist; weight falling at joist.
3. Gage between joists; weight falling between joists.
4. Gage between joists; weight falling at joist.

Two tests were made at each location, for a total of 272 tests. For each individual test a record was plotted of amplitude of vibration as a function of time. It was observed that in every case the recommendations of the Guide Criteria were met. No attempt was made to determine numerical damping characteristics; however, it was noted that the vibrations in furnished rooms tended to decay faster than in unfurnished ones, and that the type of floor finish also appeared to affect the decay rate.

3.2.5 IMPACT TESTS ON GYPSUM WALLBOARDS [16]

These tests were conducted both to obtain data on the impact strength of gypsum wallboard, and to use these data to confirm Guide Criteria recommendations for impact resistance of interior space dividers (partitions).

Testing was required since, in spite of the widespread use of gypsum wallboard as an interior surfacing material, there were few data available concerning its impact strength, although it is known to be satisfactory from observations of its past performance. By comparing test results with the recommendations of the Guide Criteria, it was possible to determine the applicability of the following BREAKTHROUGH criteria:

> "Walls should resist the following loads with a maximum net deflection not exceeding 10 percent of total maximum net deflection or $\ell/4000$, whichever is greater, measured 24 hours after removal of the superimposed load, and with no damage to surfaces, finishes, supports, or subsystems:
>
> "An impact energy of 60 ft-lb applied horizontally at any location five consecutive times, except in the case where the wall consists of stiffening elements supporting a surface cover. In the latter case, the wall should resist the 60 ft-lb impact energy delivered five consecutive times to the surface cover coincident with the axis of the stiffening element and a 30 ft-lb impact energy delivered five consecutive times to the surface cover at any other location.
>
> "In specific cases, where local repairs of surface covers may be readily accomplished without leaving objectionable traces, using available materials and methods that do not require specialized skills, the 30 ft-lb impact energy may be reduced to 7.5 ft-lb."

The 7.5 ft-lb requirement is applicable to gypsum wallboard since it can be readily repaired.

The method of testing was similar to that described in ASTM E 72. A sandbag of known weight was allowed to swing against a wallboard and stud assembly, with the impact energy being determined by the height of fall. The wallboard was nailed to 2 x 4 studs with 2 x 4 plates top and bottom to simulate an actual partition. Various combinations of board thickness and stud spacing were employed and both regular type and Type X (fire resistant) gypsum wallboard used. (See fig. 10.)

A series of impact forces was used to determine the magnitude of the force that could be resisted by the wallboard. Three conditions were examined:[1]

1. No damage to either face of the wallboard after five applications of the impact load.
2. Damage to only the unexposed face on the fifth application of the impact load.
3. Damage to both faces with one application of the impact load.

The first of these is the one pertinent to the criterion recommendations, and 72 out of 80 assemblies tested performed satisfactorily.

---

[1] Deflections were not measured and hence the results could not be used to evaluate the deflection recommendations of the Criteria.

The other two failure conditions yielded data useful in determining the effects of variables including the type and thickness of board and spacing of studs. The tests indicated that the impact strength can be increased more effectively by increasing the thickness of wallboard rather than by decreasing the spacing of studs. As would be expected, the strength of Type X board was considerably higher than that for the regular type.

The results of tests indicated that the values established in the Guide Criteria for impact resistance were reasonable.

3.2.6 TRANSVERSE LOAD TESTS OF BEARING WALL POSITIONING DOWELS

Innovative building methods can create unusual construction problems, and while these may not be directly covered by the Guide Criteria in sections dealing with life and safety of occupants, they may pose problems of major concern.

One of the Operation BREAKTHROUGH systems used hollow core precast concrete wall panels. When these were erected they served as supports for thin prestressed concrete slabs. The slabs in turn served as a form for a

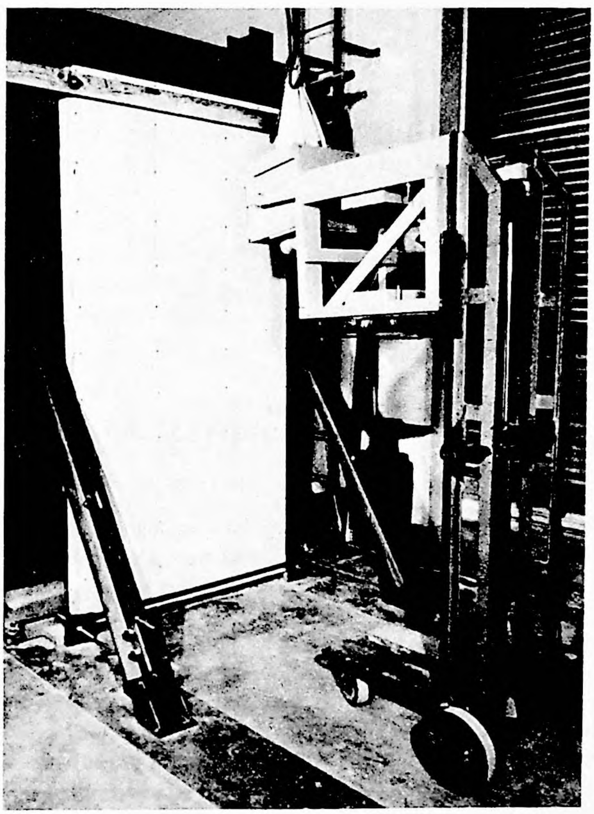

FIGURE 10
APPARATUS USED TO APPLY IMPACT LOADS TO GYPSUM WALLBOARD ASSEMBLIES

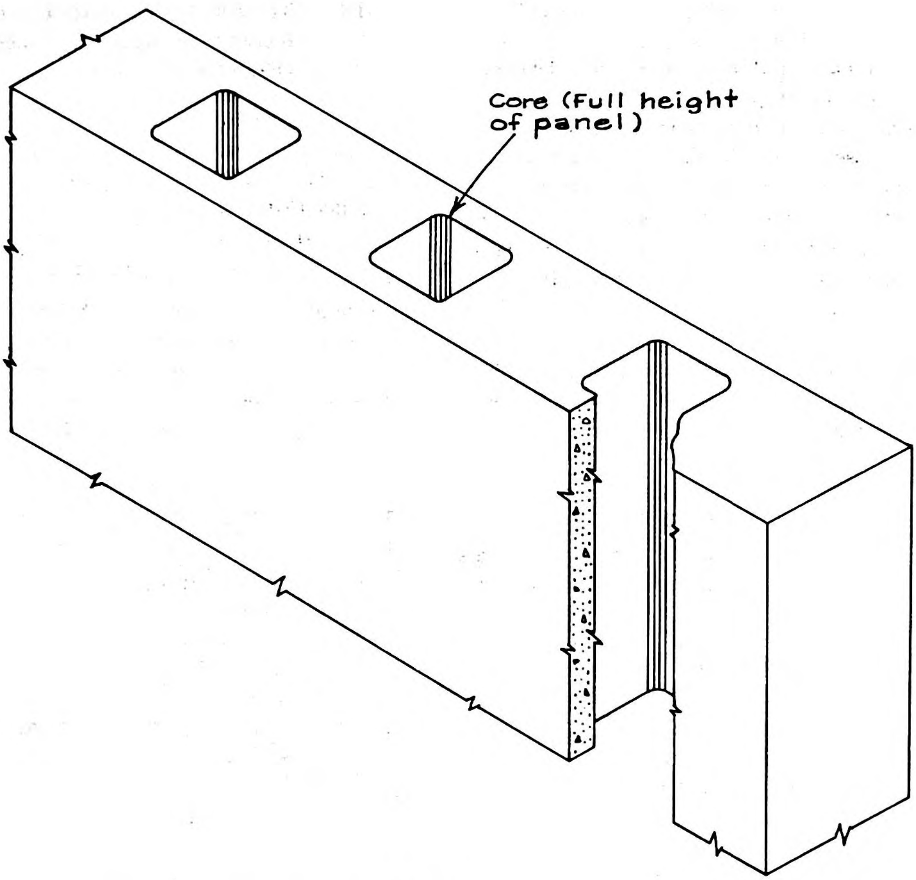

FIGURE 11
HOLLOW CORE PRECAST WALL PANEL USED IN CONCRETE BUILDING SYSTEM

cast in place concrete topping to produce a composite floor or roof. Depending on conditions, some or all of the wall panel cores were filled with cast in place concrete.

As originally planned, the panels were prevented from overturning during the construction process by positioning dowels at the bottom of the wall. The effectiveness of these dowels in providing safety during the erection process was evaluated. These tests were made to assess the merit of this procedure. The test procedure involved the application of an overturning moment to the wall with a calibrated load bar. Figure 11 shows a section through a panel.

The first series of tests evaluated dowel bars grouted into the foundation; in the second series the dowels were set, ungrouted, into slightly oversized sleeves placed in holes drilled in the support. Test results indicated that wind forces of 43 mph and 39 mph would cause overturning of the panel with grouted and ungrouted dowels, respectively. It was concluded that neither of the condi-

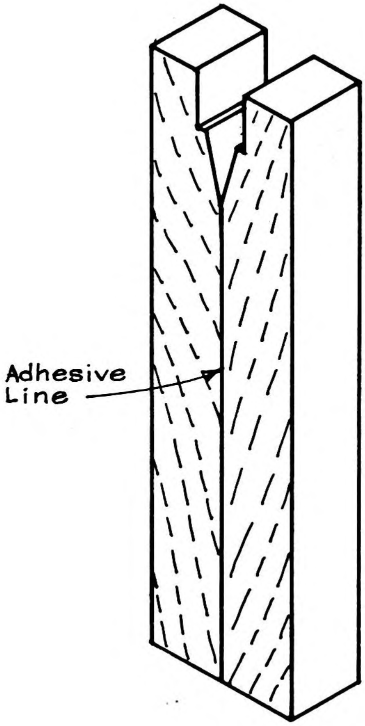

FIGURE 12
CLEAVAGE SPECIMEN
FOR TESTING ADHESIVES

tions investigated offered "any appreciable resistance to overturning." Other means of supporting the wall were developed and used for safety during construction.

3.3 STRUCTURAL MATERIALS TESTING

3.3.1 TESTS OF ADHESIVES [17], [18], [19], [20], [21]

The proposed use of adhesives in place of mechanical fasteners (nails, screws, staples, etc.) in several of the Operation BREAKTHROUGH housing systems made it important that there be knowledge as to their strength, reliability, and durability. Because of the lack of time for a lengthy study, a series of short term tests was devised to assess the long term load carrying capacity of proposed adhesives under adverse conditions.

The test specimens varied somewhat with the nature of the adhesive. The specimen for one test consisted of two blocks joined by the adhesive and was tested in shear. The specimen for the second, comprised of hardwood plies laminated with the adhesive, was also tested in shear. The specimen for the third was made from two softwood blocks connected by the adhesive and tested by splitting. (See fig. 12.) Some specimens were loaded rapidly to failure and others were subjected to long time sustained stress. Two different combinations of temperature and humidity were used. Some specimens were artifically aged in ovens with controlled temperature and humidity conditions; others were subjected to soaking and boiling.

The results were used to estimate rupture stresses after ten years for the two temperature-humidity conditions, and the estimates were used in making a judgement as to allowable design stresses.

3.3.2 EFFECTS OF EXPOSURE ON A FIBERGLASS REINFORCED POLYESTER SANDWICH PANEL

An innovative structural system employed by one Operation BREAKTHROUGH HSP used a plastic laminate assembly in walls, roofs, and interior partitions. The basic building panel consisted of two flat face sheets of chopped fiberglass reinforced polyester resin separated by a third corrugated sheet of the same material. The

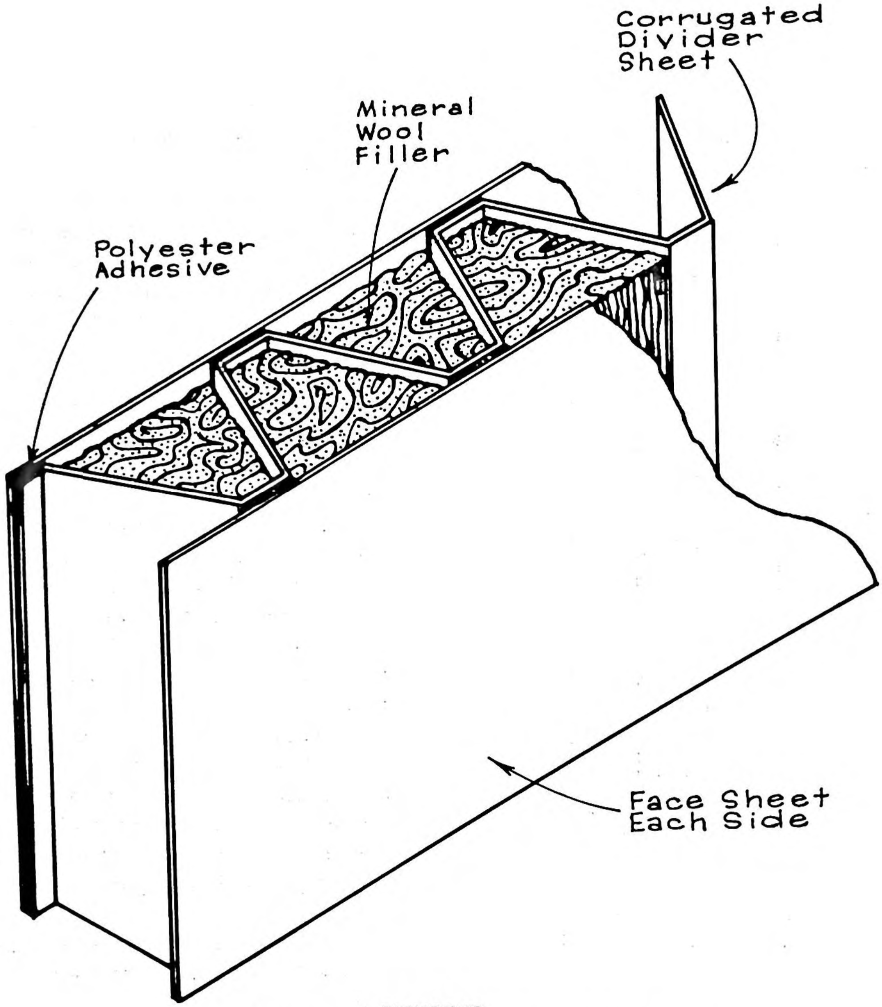

FIGURE 13
FIBERGLASS REINFORCED POLYESTER SANDWICH PANEL

three components were bonded together by a polyester adhesive. Cavities resulting from the corrugations were filled with mineral wool for insulation and fire resistance. (See fig. 13.) Wood closure pieces were used to facilitate connections at wall-roof and wall-floor junctions. Wall surfaces were sprayed with a textured coating to improve their appearance. Roof members were either coated in the factory with waterproofing material or conventional built-up roofing was installed in the field. Since there was little information available concerning the physical properties and durability of the plastic laminate these properties required investigation, as did the adhesive used to join the components. The testing included:

1. Tensile strength tests on flat face sheets to determine:

   a. Tensile strength, modulus of elasticity, and variability with 25 specimens cut parallel to the principal axis and 25 cut perpendicular to that axis.

b. Tensile creep strength at 24°C (75° F) and 50% relative humidity.

c. Tensile creep strength at 71°C (160° F) and 100% relative humidity.

2. Shear strength tests of the adhesive bond to determine:

a. Shear strength at 24°C (75° F) and 50% relative humidity. (This test included measurements for determination of the shear modulus.)

b. Shear strength after accelerated aging in accordance with Cycle A of ASTM C 481. [22].

c. Shear strength under constant load at 24°C (75°F) and 50% relative humidity.

d. Shear strength under constant load at 71°C (160°F) and 100% relative humidity.

Test 1.a was carried out in accordance with ASTM D 638 [23]; tests 1.b and 1.c, ASTM D 674 [24]; tests 2.a, 2.b, 2.c, and 2.d, ASTM C 273 [25]. Specimens for the high moisture exposure condition tests were enclosed in a heated cabinet containing water whose evaporation provided the 100% relative humidity. Accelerated aging consisted of a series of exposures to water soaking, steam, freezing, and dry heat.

Tensile specimens were cut from flat sheets in accordance with ASTM D 638. Shear specimens were cut from the sandwich panels at the intersection of the core and face sheets and placed between two steel plates in a manner similar to that described in ASTM C 273.

The results of the tensile tests of the laminate were quite consistent and indicated that the orientation of the test specimen was not important. At room temperature and humidity the strength under constant creep load was reduced about 10 percent, but at 71°C (160°F) and 100% relative humidity, a significantly greater strength reduction was experienced.

Shear strength and modulus were reduced about 30 percent by the accelerated aging process. Long term loading at room conditions [24°C (75°F) and 50% relative humidity] reduced the strength of the adhesive bond considerably and in the hot and wet condition [71°C (160°F) and 100% relative humidity], there was no significant strength left after ten continuous hours of loading.

The information obtained was used to assess the durability of the laminating adhesive and to set allowable stresses for design.

3.4 TESTS OF CONNECTION DETAILS

3.4.1 EVALUATION OF THE COLUMN CONNECTIONS USED IN A PRECAST CONCRETE MODULAR HOUSING SYSTEM [26]

Innovative construction details require special consideration particularly when they involve materials whose properties are not well known or whose interaction has not been investigated. This program was carried out to study the behavior and strength of a column connection system used between prefabricated housing modules.

One of the systems included in Operation BREAKTHROUGH used precast concrete box modules that were stacked in a checkerboard

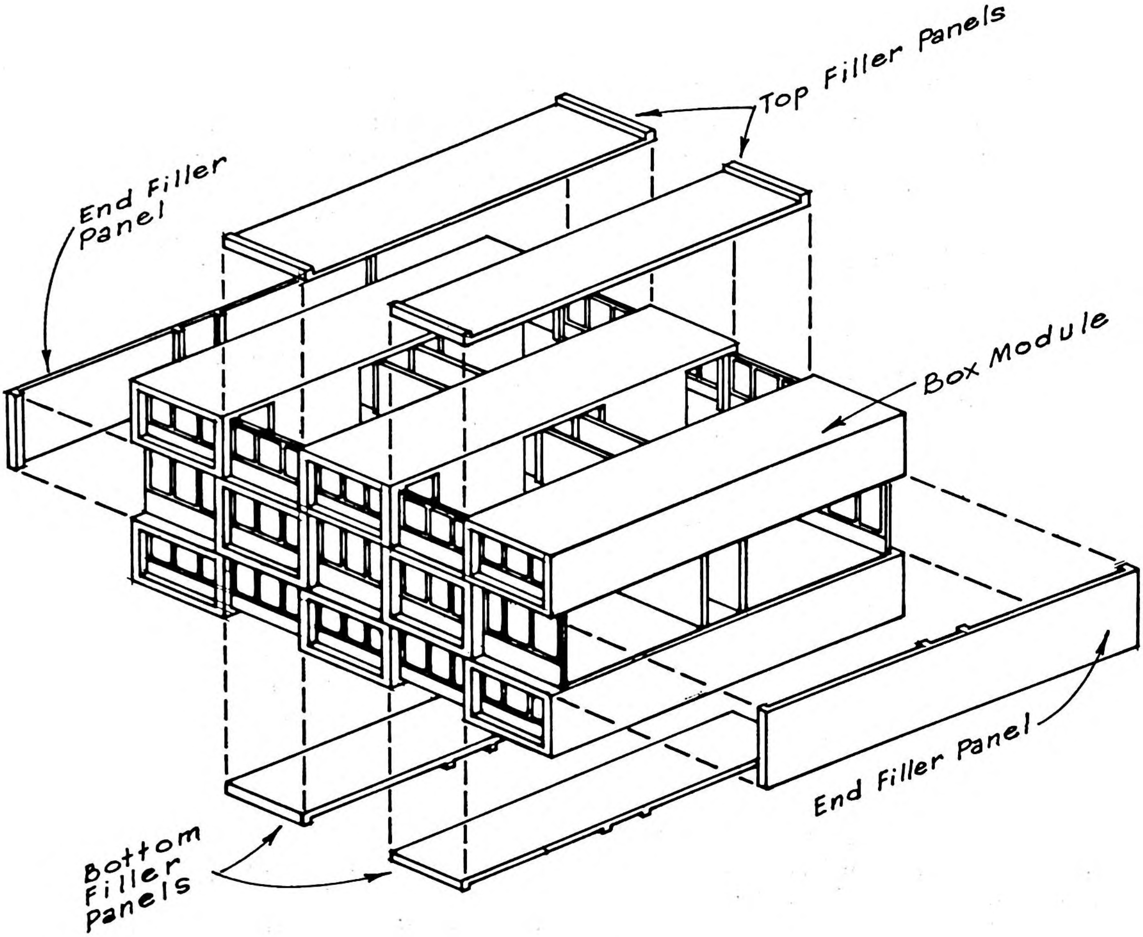

FIGURE 14
ASSEMBLY OF PRECAST UNITS IN CONCRETE MODULAR HOUSING SYSTEM

fashion to form a completed building. (See fig. 14.) The thin side walls of the module were non-load-bearing and vertical forces were transmitted through columns located at the corners of the modules and either side of the corridor. The columns were heavily reinforced and higher stresses than would normally be permitted by governing building codes were used at the bearing at the lower end of the column. This was justified by confinement reinforcement in the lower portion of each column (near the bearing). Bearing stresses were transmitted from the columns of one module to those of the module immediately below through neoprene pads. Compressive bearing stresses were considerably higher than those normally used with neoprene. Resistance to any uplift and also to horizontal shear was provided by a grouted dowel crossing the horizontal joint. (See fig. 15.)

Since the proposed design involved innovative features whose adequacy could not be determined by analysis based on

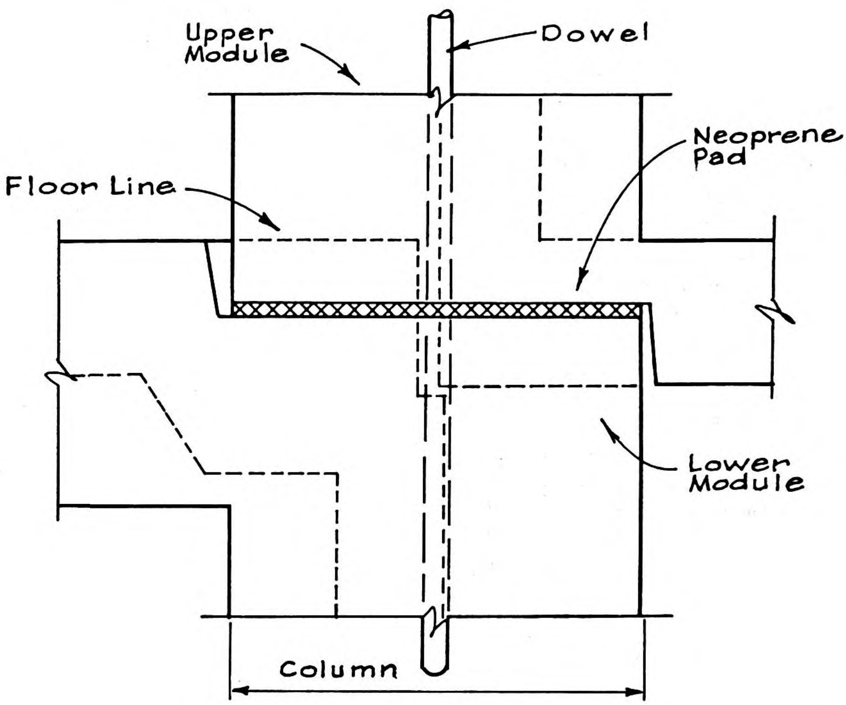

FIGURE 15
DETAIL OF COLUMN CONNECTION IN PRECAST CONCRETE BOX HOUSING SYSTEM

current standard practice, it was necessary to verify the design assumptions by a series of tests that included:

1. Tests to determine the strength of column connections with various types of bearing materials.
2. Tests to determine the physical properties of neoprene pads.
3. Tests to determine the bearing capacity of joints with steel-neoprene sandwich bearings and a grouted joining dowel.
4. Tests to determine the shear capacity of the column connection, including the effects of load reversal.

The first series of tests was designed to investigate the effects of the bearing material on the load capacity of the columns. One feature that required special attention was the effect on the concrete of the high compressive stresses in the neoprene pad. This was necessary because the deformation of the neoprene perpendicular to the columns exerts a splitting force on the concrete. The effects of eight types of joint material were studied. Test specimens consisting of two short columns were then loaded in axial compression in a testing machine. (See fig. 16.) Results indicated lower strength for a joint with a plain neoprene pad than for an unconfined concrete bearing. They also indicated that steel-neoprene sandwich pads would give higher strength than plain neoprene, provided that the steel in the sandwich did not yield during the test; friction between the concrete and steel created a confining force that reduced the tendency of the concrete in the column to split.

The second series of tests was performed by loading the neoprene pads between steel bearing blocks. Both full and half size pads were used. Compressive and radial tensile deformations were measured and moduli of elasticity determined from the observed data. (See fig. 17.) Results indicated that the modulus of elasticity of the neoprene increased considerably with increased load. Deformations for the full size pads were significantly smaller than those for the half size pads indicating that the shape of the pads is an important factor. Deformations perpendicular to the axis of loading were substantial but not uniform.

The third series of tests was similar to the first, except that only a neoprene-steel sandwich was used for bearing and a grouted dowel, like that proposed for use in the building system, joined the two columns. The load bearing capacity of the assembly exceeded that of the testing machine; however the test did indicate a higher strength than that obtained for the joints used in the first series. Although the dowel probably yielded, this apparently had no significantly detrimental effect on the strength of the joint.

The shear tests were intended to investigate the ability of the bearing joint with a grouted dowel to transfer lateral load.

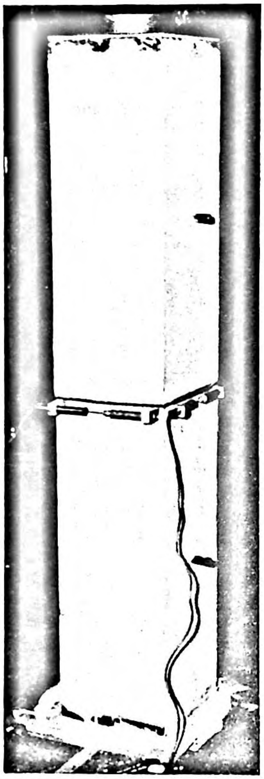

FIGURE 16
SHORT COLUMN SECTION
USED TO TEST JOINTS IN PRECAST
CONCRETE HOUSING SYSTEM

Three short column sections were assembled end to end with neoprene and with steel-neoprene joints. An axial compression was applied by a loading yoke. The center section was pushed down by a testing machine while the end sections were restrained. In some tests the direction of loading was reversed cyclically. (See figs. 18 and 19.) Test results provided the allowable design shear capacity per joint. Ductile failure was observed in both monotonic[1] and cyclic[2] loading.

[1] Single direction

[2] Reversed direction

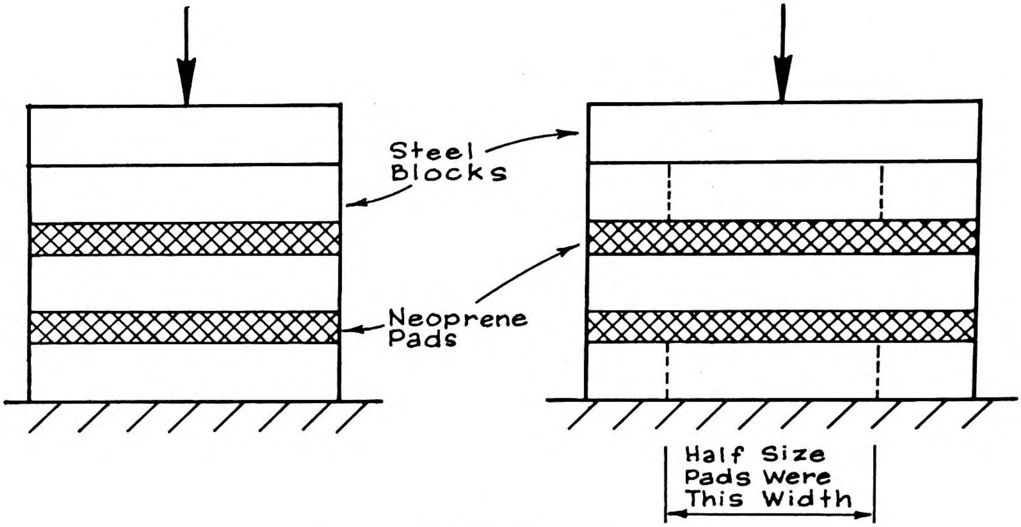

FIGURE 17
COMPRESSION TEST OF NEOPRENE BEARING PADS USED IN COLUMN CONNECTION DETAIL OF HOUSING SYSTEM SHOWN IN FIG. 14

FIGURE 18
COLUMN SPECIMEN IN TESTING MACHINE

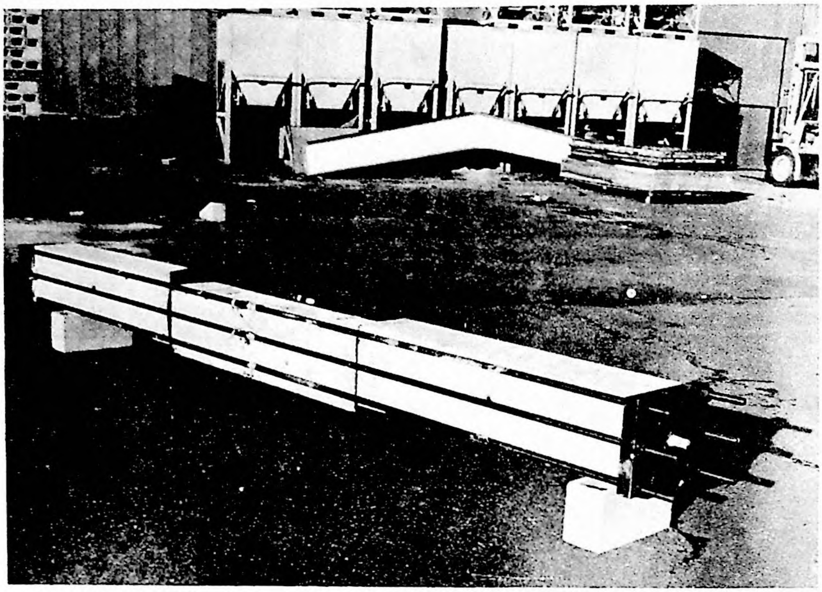

FIGURE 19
COLUMN TEST SPECIMEN REMOVED FROM TESTING MACHINE

These tests were not concerned with any one criterion but rather with the entire concept of structural serviceability and safety. They furnished valuable information regarding the compressive and shear capacity of the proposed joints that was useful in evaluating the system. They also supplied data as to the relative merits of several different joint materials, and thus provided a basis for selecting that with the most desirable properties.

3.4.2 STRUCTURAL TESTS OF MECHANICAL CONNECTORS FOR CONCRETE PANELS [27]

Innovative construction details may require physical testing, even when conventional materials are used. Tests of such connections, even if not related to a specific criterion, can be important to the entire concept of the structural behavior of a system.

One Operation BREAKTHROUGH system to which this applied used large precast concrete wall, floor, and roof panels with bolted steel interpanel connecting elements. These elements were very important because they furnished the primary structural connection between the panels and were designed not only for the transfer of static loads but also of wind and seismic loads that were to be carried through the floor diaphragms to shear walls. (See fig. 20.) Since there was no standard test for the features to be investigated, methods were devised to simulate the loadings for which the system was designed. Small sections of finished, full size concrete elements were used as test specimens during simulated loading. Electronic instrumentation was used to measure and record loads and deformations.

Several types of connections were used in the building system. Type A floor connections (see fig. 21) were used in tension, principally where the ends of two

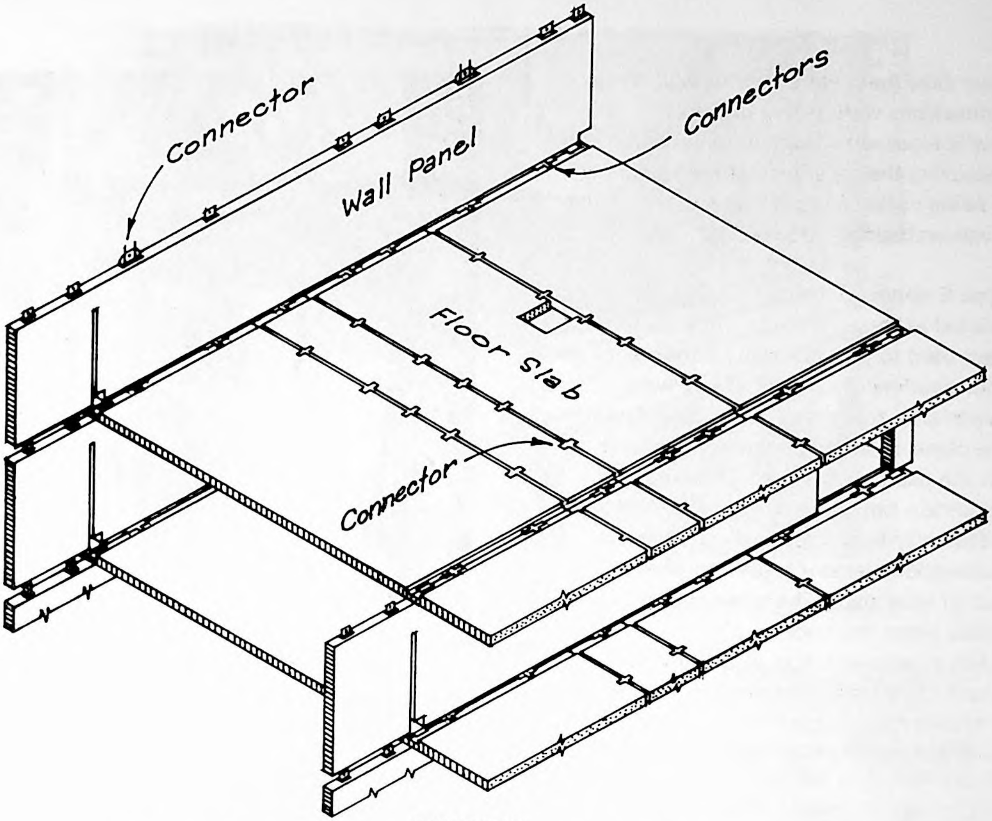

FIGURE 20
ASSEMBLY OF UNITS IN PRECAST CONCRETE PANEL HOUSING SYSTEM

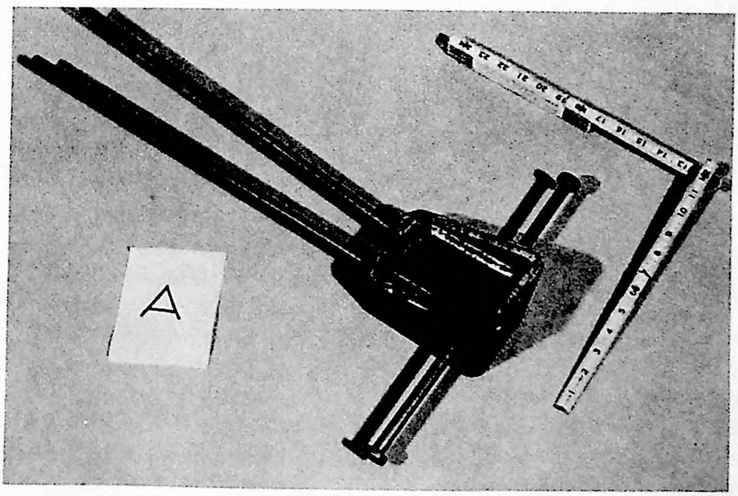

FIGURE 21
TYPE A INSERT USED IN CONCRETE HOUSING SYSTEM

floor slabs met over a bearing wall. These connections were tested by applying tensile loads with jacking frames and measuring the resistance of the anchorage to being pulled from the concrete in which it was embedded. (See fig. 22.)

Type B connections (see fig. 23) were located at the edges of the floor slabs and were used to join one slab to another or to a longitudinal shear wall. They were required to transmit vertical shear (across the plane of the slab) and horizontal shear (in the plane of the slab). The first condition can occur when one slab is loaded differently from the other, or when the connection element is used to aline an out of level slab. The other condition can occur when the floor diaphragm carries wind or seismic forces in the horizontal plane. The friction connection between abutting connecting elements was made with high strength bolts in oversized holes.

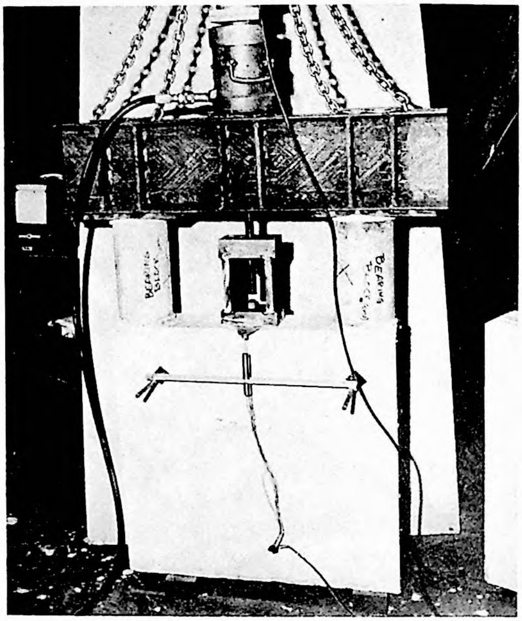

FIGURE 22
TESTING CONCRETE HOUSING SYSTEM
INSERT SHOWN IN FIG. 21

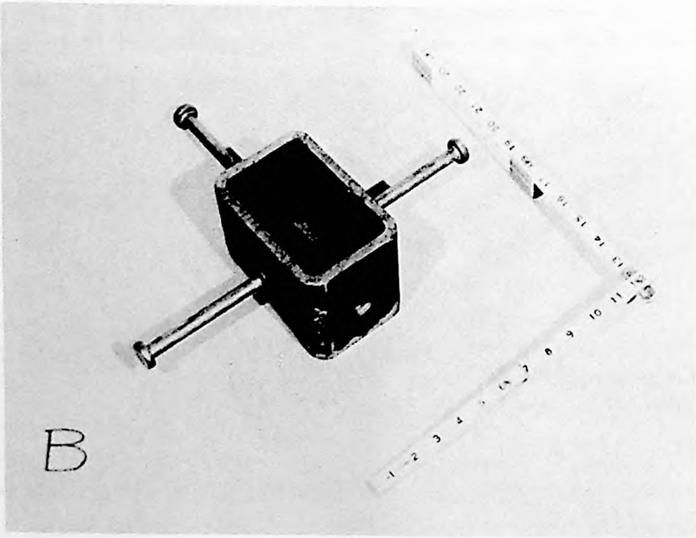

FIGURE 23
TYPE B INSERT USED IN CONCRETE HOUSING SYSTEM

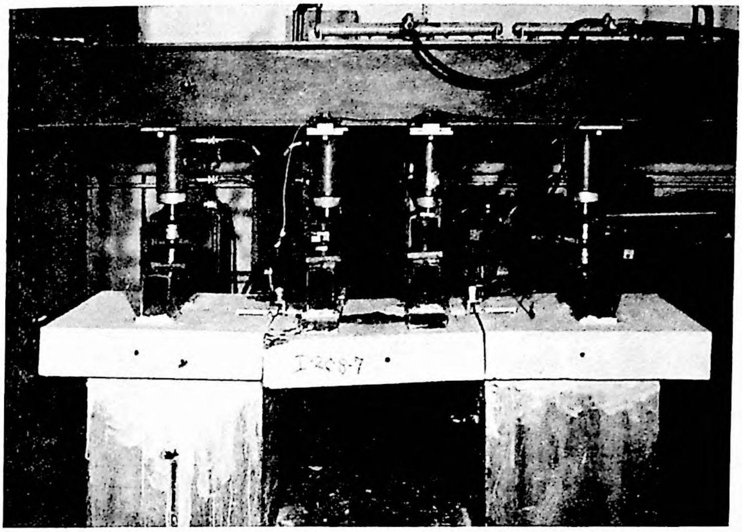

FIGURE 24
TESTING HOUSING SYSTEM INSERT SHOWN IN FIG. 23 (VERTICAL SHEAR)

The first test, on the Type B element, measured tensile pull out resistance by a method similar to that used with Type A connections. Vertical (out of plane) shear tests were conducted on specimens constructed to represent portions of three side by side slabs joined at their edges by Type B connectors. The center slab was pushed down while the others were restrained. (See fig. 24.) Similar specimens were used for investigation of horizontal (in plane) shear resistance. They were tested with the slabs in a vertical plane; the outer slabs were supported near the juncture with the center slab so as to minimize rotation and produce as closely as possible a pure shear loading condition. (See fig. 25.) When the center slab was pushed down, the vertical force was resisted by friction at the interfaces until slip occurred. Ultimate failure during this test was caused by shearing of the bolt.

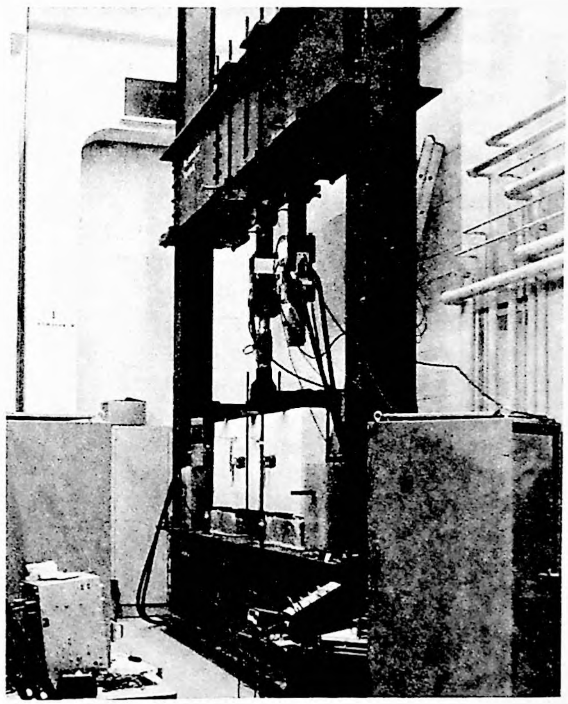

FIGURE 25
TESTING HOUSING SYSTEM INSERT
SHOWN IN FIG. 23 (HORIZONTAL SHEAR)

In addition to these static load tests, two cyclical load tests were performed on the Type B element. Neither the first test,

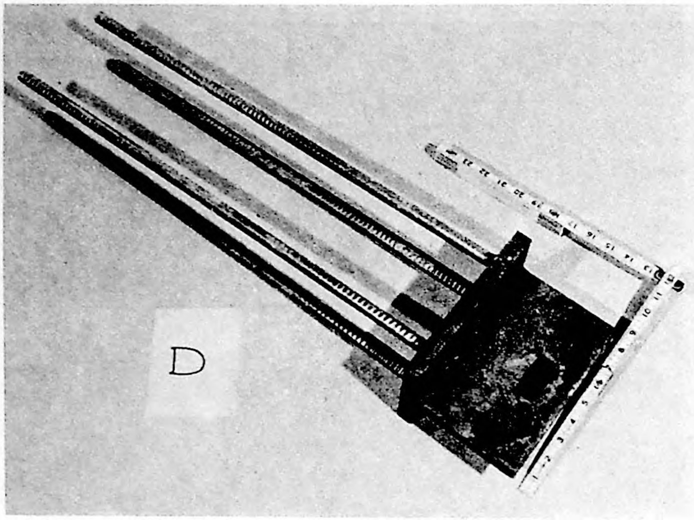

FIGURE 26
TYPE D INSERT USED IN A CONCRETE HOUSING SYSTEM

intended to represent 1,000 cycles of 50 percent wind load, nor the second, whose magnitude was based on five alternating cycles of the design seismic load, caused failure.

Type D wall connectors (see fig. 26) were used, in conjunction with Type A, to join floor slabs and bearing walls. Because of the Guide Criteria recommendations for prevention of progressive collapse, the ability of the Type D connectors to resist shear forces acting perpendicular to the face of the wall was critical. The test specimen for the Type D element was in the form of an H, with the wall panel as the crossbar. Concrete members representing the floor slabs formed the verticals. Load was applied to the wall near the face of the slabs. Failure occurred when the connection started to shear through the concrete.

Type E and F connectors transferred tension between two successive stories of wall panels. Figure 27 shows an assembly which also includes a Type A connector.

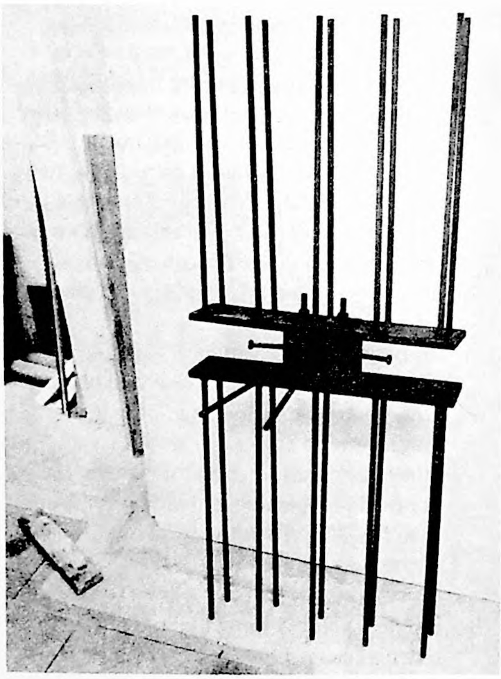

FIGURE 27
ASSEMBLY OF INSERTS USED
TO CONNECT WALL AND FLOOR PANELS
IN A CONCRETE HOUSING SYSTEM

In testing the Type E connector, a tensile load was applied to the bolts at the top of the connector (see fig. 28), whereas in testing the Type F connector, the load was applied to bolts simulating those from a Type E connector. (See fig. 29.) Failure occurred either by breaking the bolts or stripping the threads.

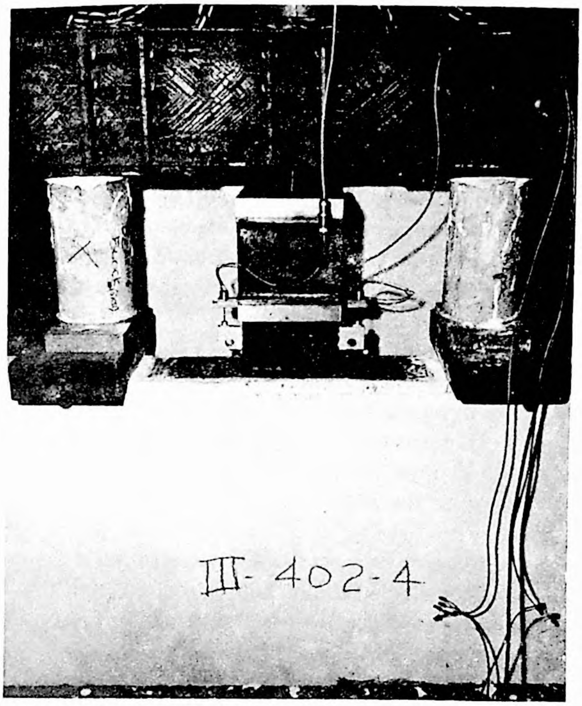

FIGURE 28
TESTING TYPE E INSERT
USED IN CONCRETE HOUSING SYSTEM

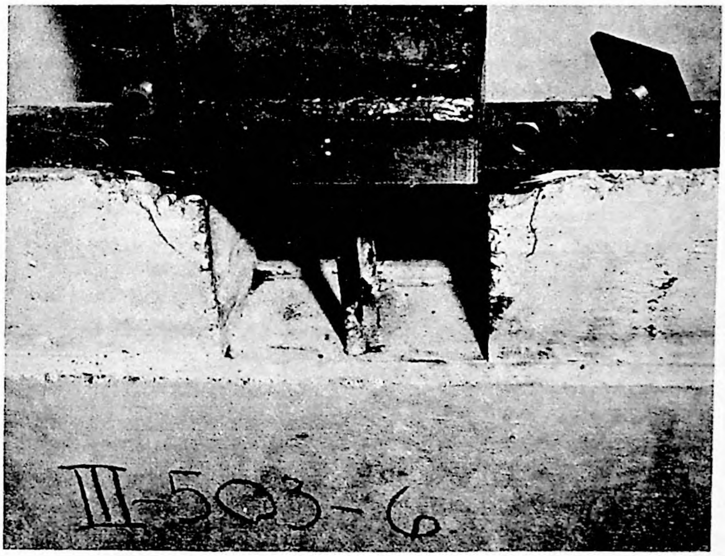

FIGURE 29
TESTING TYPE F INSERT USED IN CONCRETE HOUSING SYSTEM

3.4.3 CORE BOND TESTS OF HOLLOW CORE BEARING WALL PANELS

The fill cast in the cavities of the hollow core walls described in section 3.2.6 was reinforced with deformed bars. This testing was performed to determine the load carrying ability of the composite sections, particularly with respect to the bond between the precast panels and the cast in place fill. Since the panel cores tapered, there was a possibility that shrinkage of the fill might prevent it from sharing the applied load. The specific test objectives were to determine:

1. The strength of the bond between the reinforcing bars and the concrete fill used in the panel wall cavities.
2. The bond between the concrete fill in the cavities and the concrete of the cavity walls.
3. The effects of the type of cavity surface preparation on the bond strength between the cavity walls and the cavity core concrete.

Four experimental variables introduced into the testing program were:

1. The type of cavity surface preparation prior to filling the cavities with concrete.
2. The type of cement used in the concrete fill mix.
3. The consistency of the concrete fill mix as measured by a slump test.
4. The method of placing the concrete fill in the cavity.

The test specimens consisted of 11 pairs of cavities prepared in two full scale walls. Each pair had a different type of cavity surface treatment varying from no treatment to sandblasting. Type III cement [28] was used to fill all but one pair, in which chemically expansive cement was used. Fill mix slumps varied from 3 to 6 inches and the concrete was placed by pumping and by hand shoveling in combination with vibration. Reinforcing bars, set in the concrete fill, extended above the top of the wall.

A tensile test load was applied to each bar using a special loading frame and jack. The bar was held by a gripper reacting against an angle welded to the top of the frame. (See fig. 30.)

Strains were measured to determine if the bar yielded or was failing in bond, or if the core fill was being pulled out of its cavity.

Only six of the prepared cores were tested because of mechanical difficulties. The cores tested had only water cleaning and wetting. Since no failure occurred, it was concluded that no treatment other than water washing is needed. This test demonstrated the adequacy of the proposed details.

3.4.4 GYPSUM BOARD SHEAR PANELS

Walls faced with gypsum board are widely used in house construction. Unfortunately, there has been little engineering information available relating to the shear resistance of these walls, particularly with respect to the effects of moisture and the type of joint and fastener. This series of tests was conducted by one of the HSPs to obtain basic performance data required for the design of one of the BREAKTHROUGH wall systems.

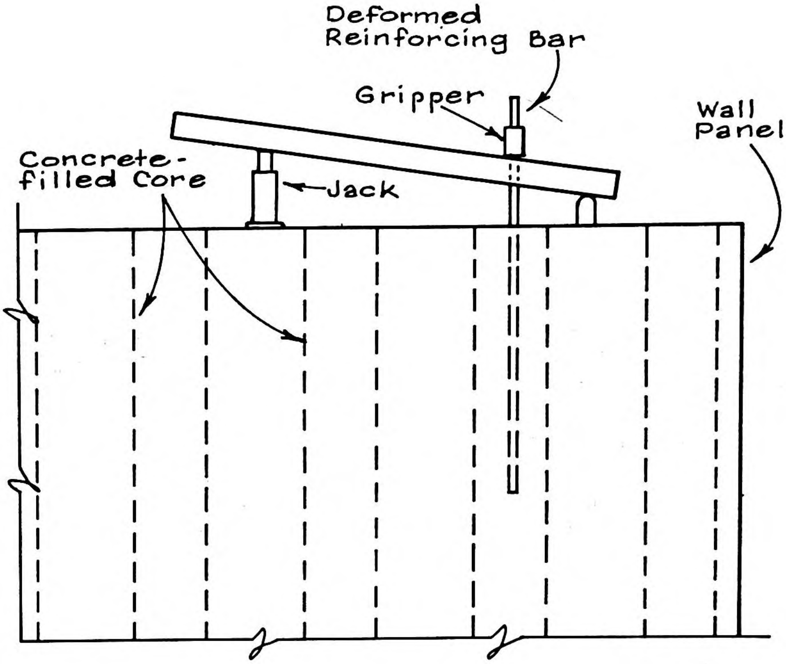

FIGURE 30
PULL OUT TEST OF REINFORCING BAR IN HOLLOW CORE WALL

Sixty-one gypsum wallboard faced panel assemblies with various joint treatments were loaded in shear in a testing machine. Most panel assemblies had steel framing, although some were framed with wood. Self tapping steel screws were used to fasten the gypsum board to the light gage steel stud frames and screws were sometimes used with wood frames in place of the conventional nails. Three different fastener spacings were employed, both with and without adhesives. Some panels were tested under room dry conditions. Triplicate samples of others were conditioned at three different moisture levels prior to testing. Test joints were either untreated, taped in the standard manner, or joined with a tapeless system.

Test results indicated that the steel screws provided strengths comparable to those obtained with nails, that the capacity of an individual screw is not affected by the fastener spacing, and that adhesive bonding greatly increases the stiffness of a panel assembly with untreated joints but does not add appreciably to the stiffness of assemblies with treated joints. The wetted specimens were much weaker and less stiff than those tested in a room dry condition.

3.5 TESTS OF ASSEMBLIES

3.5.1 ENVIRONMENTAL EVALUATION OF POLYURETHANE FOAM CORE SANDWICH PANEL CONSTRUCTION [29]

The strength of a sandwich panel depends on the strength of its components, the shape into which they are formed, and the integrity of the connections joining them.

Any adverse effect on these factors could seriously interfere with the functioning of the panel, particularly removal of one of the faces or deterioration of the bond between the core and faces.

One Operation BREAKTHROUGH system employed an innovative wall panel consisting of an exterior face of 1/8 inch cement asbestos board and an interior face of 1/4 inch plywood bonded to a foamed in place polyurethane core which filled the space between them. The edges of the sandwich panels were bound with aluminum extrusions and these extrusions were joined to each other by aluminum splines and rubber wedges. (See fig. 31.)

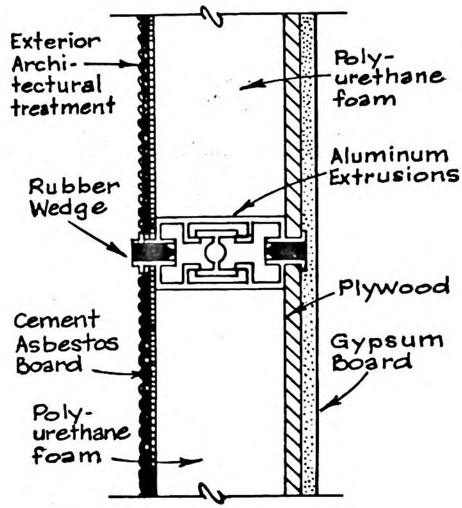

FIGURE 31
POLYURETHANE CORE SANDWICH PANEL

Analysis indicated that a well bonded sandwich panel was structurally adequate to carry the required loads, but there were no data as to the effects of temperature and humidity on the core and on the bond between the core and faces. This is important since the foam core contributes lateral restraint to the faces and thus increases their load carrying ability. Therefore, if the bond of the faces to the core is destroyed or weakened the panel assembly will also be weakened. These tests were performed to determine if the moisture and temperature exposure that would occur during normal service would significantly reduce the strength of the sandwich panel.

Three series of tests were performed on full scale wall panels. They are believed to be realistic simulations of in use conditions and provided usable results. The first test series consisted of exposing the exterior facings of a pair of loaded panels to a 30 day period of alternating high and low temperatures [46°C (115°F) to – 11°C (13°F)] with a corresponding change in relative humidity. The inside face of the panels, which was covered with gypsum wallboard as it would be in an actual house, was exposed to air controlled at 24°C (75°F) ± 3°C (5°F) and 62% ± 5% relative humidity. A superimposed vertical load of 2.0D + 0.5L[1] was maintained on the pair of wall panels during this period by a series of yokes. No indication of any structural problems occurred during the test.

[1] D = dead load; L = live load.

In the second series of tests the panels from the first test were loaded to failure in axial compression with maximum loads far in excess of the design loads. The bond of the faces to the core was inspected following these tests and only a small area of one panel was found to be unbonded; however, this appeared to be a manufacturing defect rather than a failure during the test. No moisture was visible in the interior of the panel.

The third test series consisted of the flexural loading of two wall panels which had been subjected to two different moisture conditioning methods. One panel was conditioned at 95% relative humidity and the other at 50% relative humidity. Following five days of conditioning, uniform loads were applied cyclically to each panel by means of airbags.

The panels were initially subjected to ten cycles of loading alternating between zero and the design wind load (25 psf)[1]. The load was then increased to 1.95 times the design wind load and was subsequently increased until failure occurred.

Failure in both compressive and flexural tests was accompanied by separation of the aluminum boundary extrusions from the panels; however, this occurred at loads well in excess of the required design load. The high humidity conditioning did not appear to have any adverse effect on the flexural strength of the wall panel.

[1] psf = pounds per square foot

These tests gave satisfactory evidence that the behavior of the wall panels in compression and flexure as well as the bond of the faces to the core would not be adversely affected by a considerable range of temperature and moisture variations. The tests also showed the necessity for good details (such as the aluminum edge extrusions); i.e., unless the strength of the extrusions is adequate to develop that of the assembly of which they are a part, a detail may control the useful capacity of the entire system.

3.5.2 STRUCTURAL TESTS FOR A HOUSING SYSTEM USING SANDWICH PANELS WITH GYPSUM BOARD SURFACING [31]

One of the Operation BREAKTHROUGH systems employed innovative panels consisting of paper honeycomb cores faced with fiberglass cloth reinforced polyester resin for roof, wall, and floor members. This sandwich was the basic structural element for the entire housing unit. Both faces, except for floor panels, were covered with gypsum wallboard for physical and fire protection. Plywood was used as the upper (walking) surface of floor panels in place of gypsum board. Exposed surfaces of exterior wall panels were protected with a coating of chopped glass fibers and polyester resin followed by an application of fine aggregate. Wood closures were

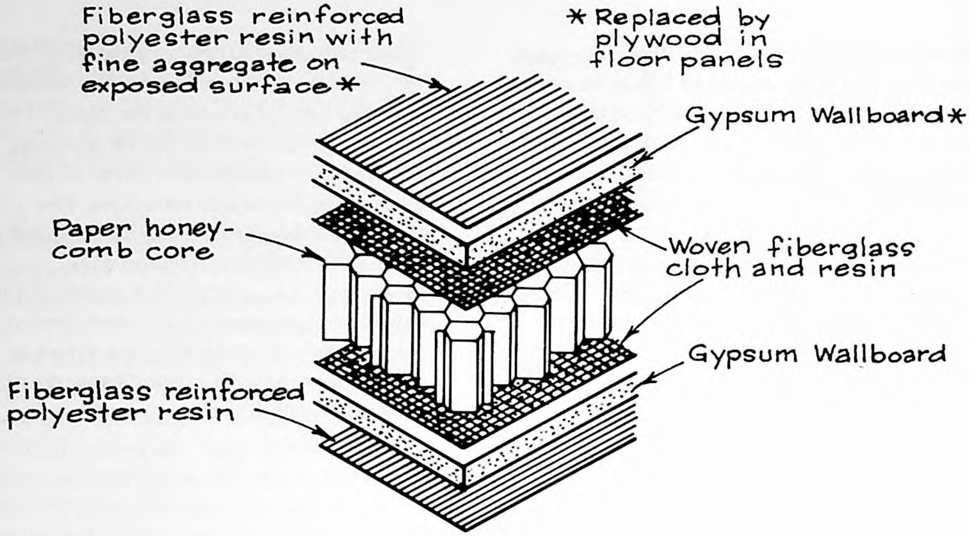

FIGURE 32
HONEYCOMB CORE PANEL WITH GYPSUM WALLBOARD FACING

provided around all panels and an adhesive was used to join the panels. (See fig. 32.)

Since little was known about the materials involved, it was necessary to make several tests to be able to predict the behavior of the panels and the bonded connections between them.

Features that required investigation were:

1. The compressive strength of wall panels.
2. The behavior of floor and roof panels under short term and long term flexural loading.
3. The bond between the fiberglass reinforced facing and the core.
4. The strength of the bonded connections between panels under repeated loading.
5. The effects of moisture on strength.

These tests encompassed the entire concept of structural safety and serviceability rather than being directed toward any single criterion. Testing for compressive strength was in general accordance with ASTM E 72, with precautions being taken to apply the load directly to the reinforced polyester facings and not the core. Both concentric and eccentric loadings were used and panel shortening and lateral displacement measured with appropriate electronic apparatus. Short wall panels, the behavior of which would give a better indication of the compressive strength of the assemblies without the effect of column action, were tested in a similar way but without eccentric loading or measurement of lateral deflection. Short term loading of floor and roof panels was applied with airbags inflated against the lower surface (actually, the top) of inverted panels. After five cycles of loading the panel was loaded to failure.

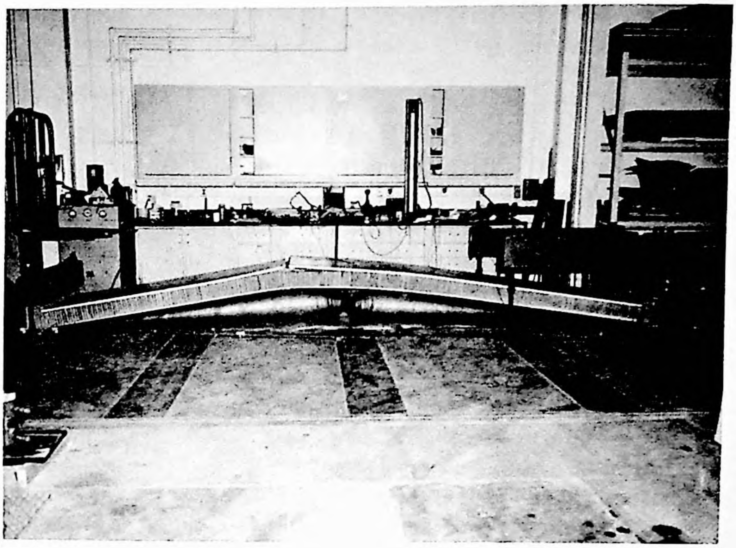

FIGURE 33
PANEL FLEXURE TEST
(IN INVERTED POSITION)

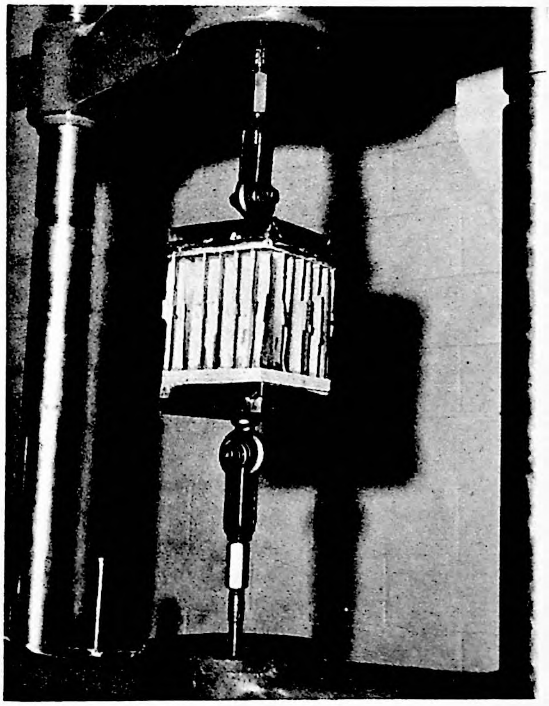

FIGURE 34
TRANSVERSE TENSILE TEST OF
PANEL SHOWN IN FIG. 33

(See fig. 33.) Deflections were measured and recorded throughout the test. Results of this test showed that the ultimate capacity of the panels was about three times the service load, and that the behavior in flexure was quite elastic.

The strength of the bond between core and facing was measured on specimens cut from floor panels which had previously been tested for flexure. These specimens were loaded in direct tension in accordance with ASTM C 297 [32]. (See fig. 34.) Joint strength was tested in a special apparatus which incorporated a double acting hydraulic jack used to increase and decrease the angle between two connected members. Loading was applied in cycles until failure took place. The specimens were tested in two conditions–one after being conditioned at 23°C (73°F) and 50% relative humidity and the other at high temperature and humidity [71°C (160°F) and 95% relative humidity.] (See fig. 35.)

The last test evaluated the ability of roof and floor panels to sustain long term loads. Relative humidities and deflections were observed for a period of about ten months during which time a constant load was applied with sand. No "aged" specimen was included in this phase of the testing.

The results of these tests yielded direct design data for the tensile strength of the adhesive, compressive strength of wall panels, fatigue resistance of joints, and effects of moisture on these strengths. Data from the flexural tests are not directly applicable to the real structure because the specimens were relatively narrow whereas the actual panels are very wide and act more as two way slabs supported on four edges. However, the test results did allow a determination of the behavior of the various structural elements with respect to the serviceability and safety criteria to be made.

3.5.3 STRUCTURAL TESTS OF HOUSING COMPONENTS OF FIBERGLASS REINFORCED POLYESTER LAMINATE [33]

The innovative panel described in section 3.3.2 and shown in figure 13 also required testing to determine its structural properties. The sheets themselves were an innovative building material, the strength of the adhesive joining them had to be evaluated (some study of this was made in the tests reported in section 3.3.1), and the behavior of the assembly, while it could be calculated, had to be verified experimentally. The effects of moisture and temperature on the behavior of the panel material also required investigation. This test program was undertaken to study all these features.

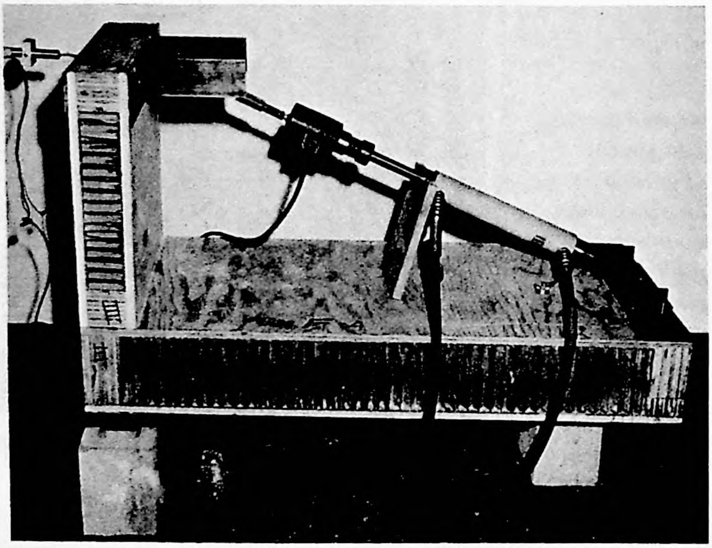

FIGURE 35
TESTING CORNER JOINT STRENGTH OF PANEL SHOWN IN FIG. 33

Testing included the following items:

1. Tensile and compressive strength of the laminated sheet and the effect of temperature and humidity thereon. (Also see sec. 3.3.2)
2. Shear strength of the adhesive bond joining the sheets and the effects of temperature, humidity, and sustained loading thereon. (Also see sec. 3.3.2)
3. Racking tests of wall panels.
4. Short and long term compression tests on wall panels.
5. Short and long term flexural tests of roof panels.

Tensile and compressive strengths were determined by methods described in Federal Test Method No. 406. [34] Specimens were subjected to varying conditions of temperature and humidity before being tested. (See sec. 3.3.2.)

The shear strength of the adhesive bond was determined on specimens cut from full panels in the area where the core was bonded to the face sheet. These specimens were tested in two ways: with short term loading applied with a testing machine, and with sustained loading applied by suspended dead weights. (See figs. 36 and 37.)

The racking tests were carried out with each of three variations of the ASTM E 72

FIGURE 36
CONTROLLED HUMIDITY CHAMBER
USED FOR TESTING STRENGTH OF
ADHESIVE USED IN PANELS WITH FIBERGLASS
REINFORCED POLYESTER SKINS

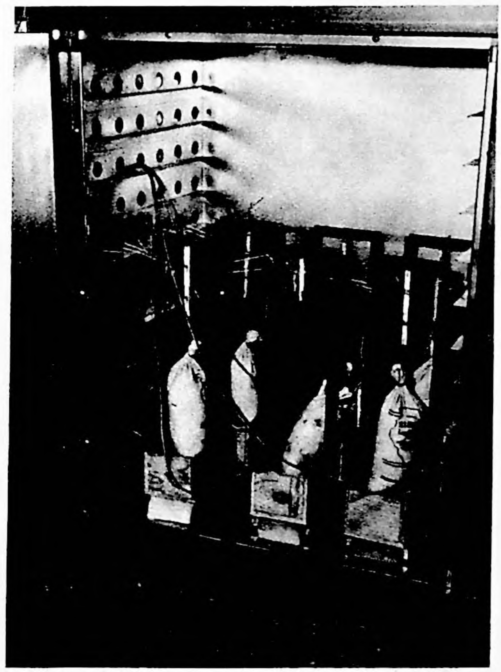

FIGURE 37
LONG TERM TENSION
TESTS OF ADHESIVE USED IN
PANELS WITH FIBERGLASS
REINFORCED POLYESTER SKINS

method. The specimen for each test consisted of a panel clamped to a frame on the laboratory floor. Racking loads were applied at an upper corner with a hydraulic ram. In the first test, no hold down was applied on the test specimen, in the second, a hold down force restrained the loaded corner; the third panel was tested with hold down forces distributed along its top edge. (See fig. 38.)

Short term compression tests were carried out by following ASTM Method E 72 with eccentric loading applied with a testing machine. The long term compressive force was applied eccentrically by spring loaded yokes. Two types of bottom support were used.

The short term flexural test of the roof panel was made by loading an inverted panel with an airbag. Three cycles of simulated service loadings were applied followed by loading to failure. Dry sand was used as the long term flexural load.

The tests of the fabricated panels indicated that they were capable of sustaining their ordinary design loads and that, by application of a suitable coefficient of variation,[1] reasonable design values could be obtained.

The wall panels had top and bottom wood plates to provide surfaces for joining intersecting members. The corrugated core did not bear against these plates and therefore vertical loads had to be transferred from the plates to the face sheets by shear on the adhesive joining them. Failure in compression and racking tests all took place at this location. This indicates the importance of fabrication details in the overall behavior of a structure. Other quality control factors such as the thickness of the adhesive were also shown to be critical in the performance of the system.

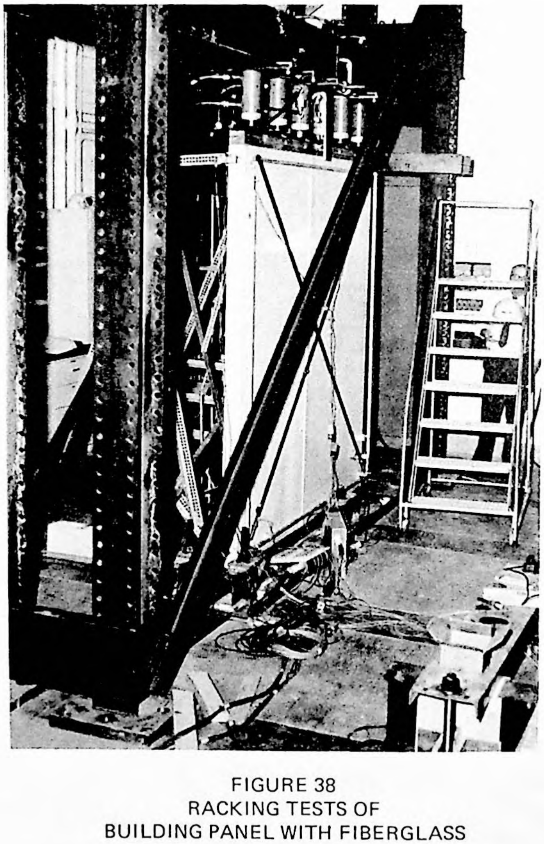

FIGURE 38
RACKING TESTS OF
BUILDING PANEL WITH FIBERGLASS
REINFORCED POLYESTER SKINS

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[1] Coefficient of variation is a measure of relative dispersal of a group of observations. Technically, it is the ratio of the standard deviation of the average of a group of observations, where the standard deviation is the absolute value of the dispersal on either side of the average value within which 68.3% of all observations will fall.

3.5.4 STRUCTURAL EVALUATION OF STEEL FACED SANDWICH PANELS [35]

An innovative housing system in Operation BREAKTHROUGH employed 3 inch thick sandwich panels for floors, roofs, and walls These panels consisted of prefinished sheet steel facings bonded to an insulated paper honeycomb core. All panels were identical except those used for floors which had an upper plywood wearing surface. Wood perimeter members were used in all panels. (See fig. 39.) The structural behavior of this type of construction is very dependent on the strength and stiffness of the component materials, with the long term strength of the bonding adhesive after exposure to varying moisture conditions being especially significant.

Since it was intended that no additional roofing membrane be used, the long term strength of the roof panel was of particular importance. For this reason, tests were made on roof panels rather than panels intended for use in walls and floors. The test program was designed to study the

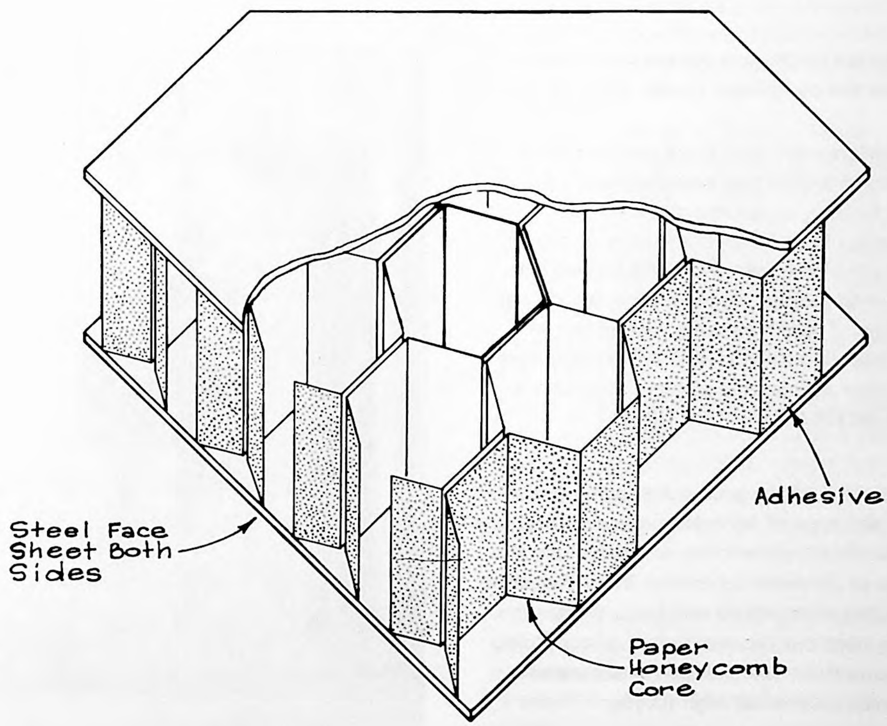

FIGURE 39
STEEL FACED SANDWICH PANEL

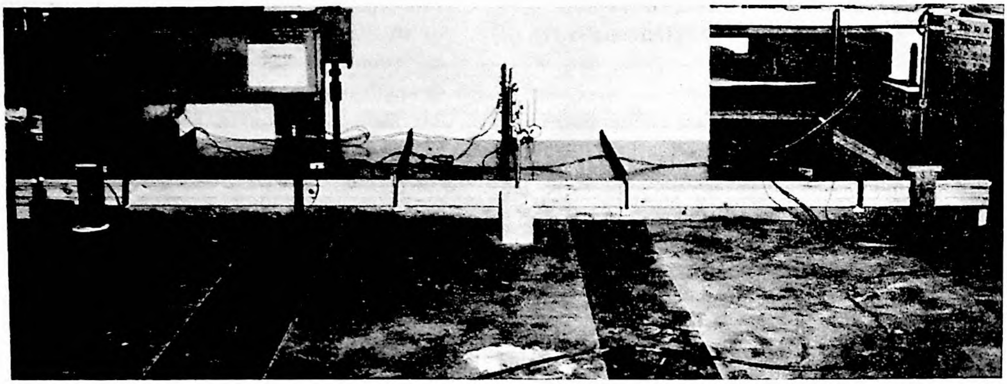

FIGURE 40
FLEXURAL TEST OF STEEL FACED SANDWICH PANEL

properties of the component materials as well as the completed panels. (See fig. 40.)

Tensile strength tests were conducted on panels, in a direction perpendicular to their facings, to determine either the strength of the honeycomb core or the strength of the adhesive bond joining it to the metal facings, depending on which was weaker. These tests were carried out in accordance with ASTM C 297 both before and after accelerated aging in accordance with ASTM C 481. (See fig. 41.)

The results of the accelerated aging indicated that one type of adhesive proposed for use in the sandwich panels was unsatisfactory because of its water solubility. The other adhesives tested appeared satisfactory after the aging tests but the coefficient of variability computed for the strength of the panel material was rather high (0.41).

Four flexural tests were conducted on full scale roof panels. Three were short term

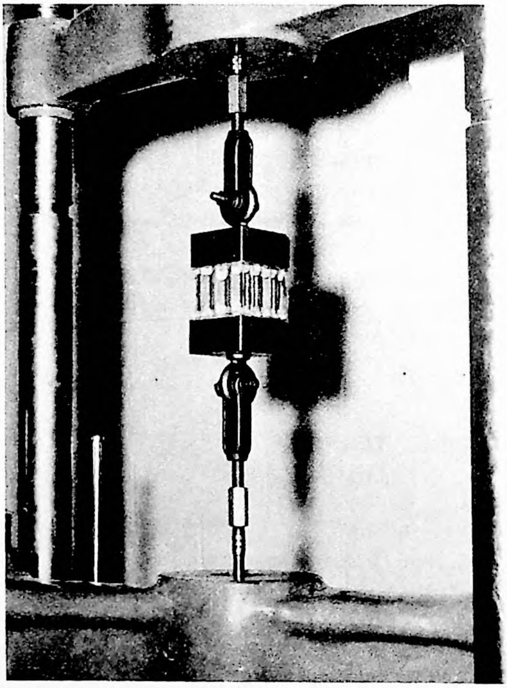

FIGURE 41
FLATWISE TENSILE TEST
OF STEEL FACED SANDWICH PANEL

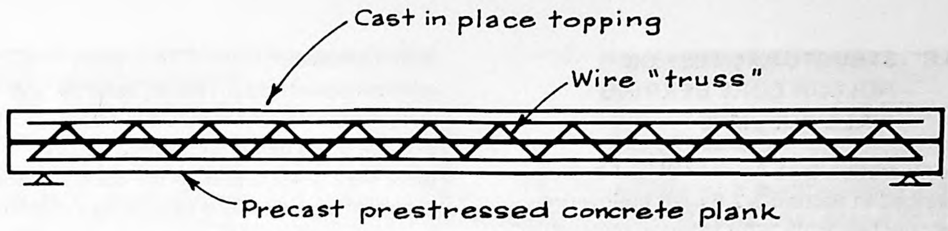

FIGURE 42
COMPOSITE FLOOR SLAB WITH WIRE "TRUSS" TIES

tests with loading applied by airbags under inverted slabs. The fourth was a 24 hour sustained load test with sandbag loading. Based on these tests, and using a variability factor of 0.41 and the recommended live load factors, an allowable load of 26 psf was determined for the roof panels. One interesting result of the tests was an indication that the panels did not exhibit a ductile type of failure.

These tests were involved with the whole general concept of structural strength and serviceability and were intended to provide the type of information that would enable a designer to form an opinion as to the suitability of this type of sandwich panel for use as a load supporting member.

3.5.5 TEST OF COMPOSITE FLOOR TRUSS SLAB

The Operation BREAKTHROUGH housing system described in section 3.2.6 and illustrated in figure 11 included a composite floor consisting of a thin, precast, prestressed concrete slab topped with cast in place concrete. As originally planned, the precast elements were to be three inches thick with exposed vertical wire "trusses" providing anchorage into, and composite action with, the cast in place concrete topping. The tests described here were intended both to evaluate a design change in which the trusses were omitted and to study the behavior of a precast plank element with topping, particularly with respect to ultimate load capacity, deflection, and permanent deformations. (See fig. 42.)

Concrete toppings of three different strengths were cast on three sample slabs; no special surface treatment was used prior to placing the topping. Testing was carried out in accordance with Section 18 of ASTM E 72 with quarter point loading applied through several cycles. Appropriate records were made of loads, deflection, and recovery.

Two of the three slabs tested were loaded to failure. Deflections for all three slabs were approximately $\ell/500$[1] under full design load, and a permanent deformation of $\ell/2100$ was determined for the slab that did not fail. These tests indicated that the composite slab without "trusses" was adequate to carry the design loads without excessive deflections, which was important since the omission of the "trusses" resulted in considerable cost savings.

[1] ℓ = span measured center to center of supports.

3.5.6 STRUCTURAL TEST ON HOLLOW CORE BEARING WALL COLUMNS

The Operation BREAKTHROUGH system described in section 3.2.6 used hollow precast concrete walls with tapering rectangular holes. The latter were intended to be filled with cast in place concrete subsequent to erection. The load carrying capacity of this type of member, particularly with respect to the bond between precast and cast in place concrete, and the sharing of the load between them, was unknown. Consequently, it was necessary to investigate this by testing. (Also see sec. 3.4.3.)

Six wall specimens were included; three had no concrete fill and three were filled in the laboratory with transit mixed concrete. All specimens were tested in compression in accordance with ASTM E 72 with a load eccentricity of 1/3 of the wall thickness. Special fittings were used to apply the loads. Vertical shortening and lateral deflection were measured as well as vertical loads.

The compressive strengths of the three filled walls were quite consistent; but one of the three unfilled panels had a much lower strength than the other two. The average of the filled walls was 75 percent greater than the average for the unfilled panels indicating that the cast in place core was in fact sharing the load.

3.6 TESTS OF LARGE UNITS

3.6.1 TWO STORY MODULE SIMULATED WIND LOADING TESTS

Section 3.5.1 describes the environmental testing of an innovative polyurethane foam core panel, faced with cement asbestos board and plywood, used by one Operation BREAKTHROUGH HSP. Because of its highly innovative nature there were questions as to the ability of the panels and connections to provide adequate resistance to lateral forces and to maintain the drift limits recommended by the Guide Criteria under both design load and required ultimate load. This test was made to study the effects of simulated wind loading on a small two story housing module, which was 12 ft square and constructed and anchored in accordance with the HSP's standard details. (See fig. 43.)

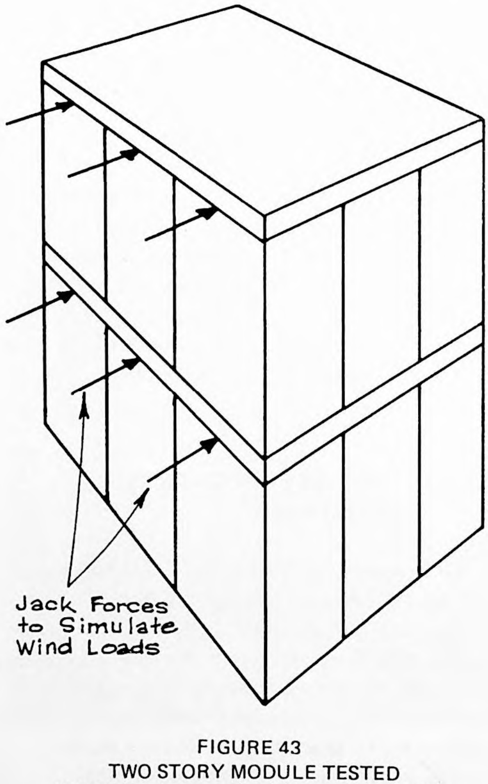

FIGURE 43
TWO STORY MODULE TESTED
FOR RESISTANCE TO LATERAL LOADS

Hydraulic jacks acting through a load distribution system were used to apply a load to one side of the module. Two different loads were applied during the test. In the first load cycle, a force corresponding to 100 percent of the design wind load was used; in the second, loading was increased until failure occurred in the spline connection between the panels at 130 percent of the design wind load.

The results indicated that the test module was capable of sustaining the required wind loads without failure; however, no statement was made concerning the drift criterion.

3.6.2 STRUCTURAL TESTS OF A WOOD FRAMED HOUSING MODULE [36]

This series of tests served two purposes:

1. To observe the effects of transportation on the structural integrity of a module.
2. To obtain engineering data concerning performance of a completed module under several types of loading.

The module chosen for study was part of a building system in many ways similar to conventional construction with wood joists, studs, rafters, sills, plates, plywood roofs and floors, gypsum board wall surfaces, etc. (An extended description can be found in Reference 36.) The test module formed the upper story of the front section of a row housing cluster constructed from several similar modules. (See fig. 44.) The left hand portion of the module was triangular in cross section, served as the

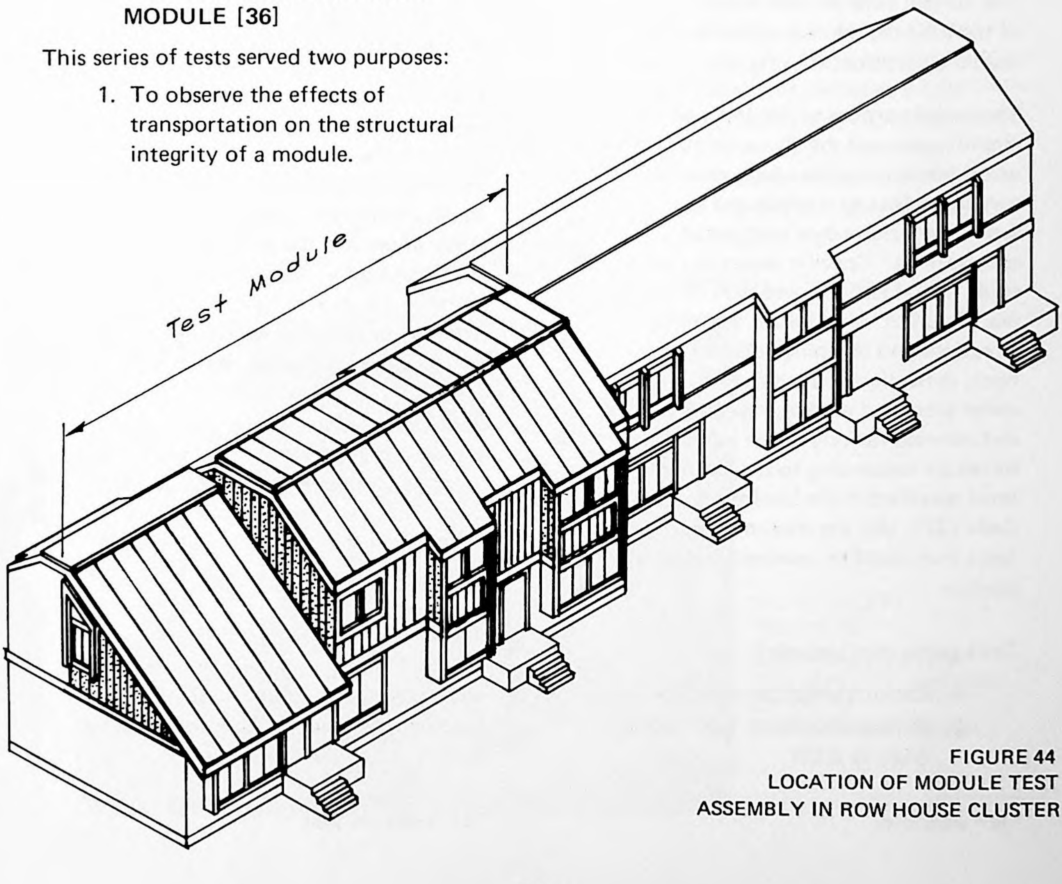

FIGURE 44
LOCATION OF MODULE TEST ASSEMBLY IN ROW HOUSE CLUSTER

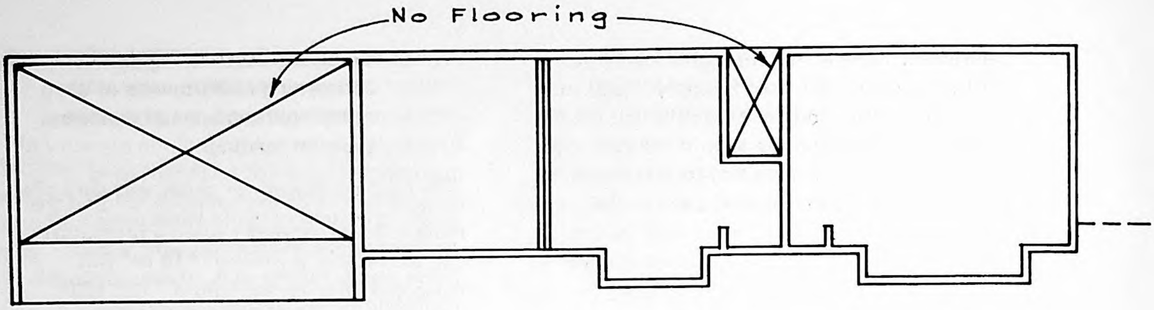

FIGURE 45
FLOOR PLAN OF MODULE TEST ASSEMBLY SHOWN IN FIG. 44

upper part of a "cathedral ceiling" living room, and hence had no floor. The balance, which contained bedrooms, was floored. The normal exterior wall formed the front of the module; the rear wall was an inter-dwelling partition. (See fig. 45.)

The stated purpose of the test was ". . .to quantify some of the characteristics of the wood framed module which were not conducive (sic) to analysis and to supplement these data with visual observations." Specific objectives were: to study lateral stiffness and drift of the module under wind forces, transient vibrations and damping behavior of the floor, deflection and recovery of the floor under sustained loading, repeated racking and reversed racking of the module by forces corresponding to the earthquake force specified in the Uniform Building Code [37], and the maximum horizontal force that could be resisted by the test module.

Tests performed included:

1. Racking under service loads (W).[1]
2. Repeated racking; 1,000 cycles 0.0W to 0.5W.
3. Reversed racking; 5 cycles, ± 1.0E at 3 frequencies.[2]
4. Racking to failure.
5. Transient floor vibrations.
6. Sustained floor load.

The first of these is directly related to recommendations of the Guide Criteria dealing with drift under service loading; the second and the third, to drift and recovery under cyclic loading; the fifth to magnitude and decay of vibration; and the sixth, to residual deflections under long term loads. The fourth is not directly related to any specific criterion and was intended to obtain information about ultimate lateral load capacity.

Observations made on the module indicated that no structural damage and only minor surface finish damage of a nature that could be easily repaired occurred during the 850 mile railway shipment.

A special procedure had to be devised to test the module in racking since there was no established method. Hydraulic rams supported by steel reaction frames were used to apply horizontal forces to the

[1] W = wind load.

[2] E = earthquake load.

module at various locations. Forces and displacements resulting from the loading were measured. Rods passing through the structure allowed for reversal of the applied force by pulling against the side of the module away from the arms. (See fig. 46.)

Floor system vibrations induced by dropping a weighted bag through a measured height both over joists and between adjacent joists were studied. Deflections were measured continuously from the time of impact.

The sustained floor loading was applied with sandbags and maintained for 24 hours. Deflections were measured during loading and after recovery.

The results of the racking tests indicated that a wind force of 21 psf could be sustained without exceeding the recommended drift ratio. The structure appeared to behave elastically under the applied load. The application of 1,000 cycles of simulated wind load did not cause any structural damage and only about 18 percent residual deflection. Fifteen cycles of simulated (reversible) earthquake loading were sustained without signs of distress. Although the maximum racking capacity of the module could not be determined because failure of the adhesive holding the module to its support caused a premature end to the test, a value of 116 psf was measured prior to the failure. The HSP subsequently changed the design to use mechanical fasteners to attach the module to its support. The vibration test data obtained indicated compliance with the Guide Criteria since decay took place within the recommended time. Deflections under sustained load and residual deflections after load removal were within the criterion recommendations.

The series of tests was very valuable in that it gave an unusual opportunity to investigate several properties of a large structural component that could not be studied adequately by mathematical analysis. The results indicated that the design of the module was adequate with respect to the factors investigated.

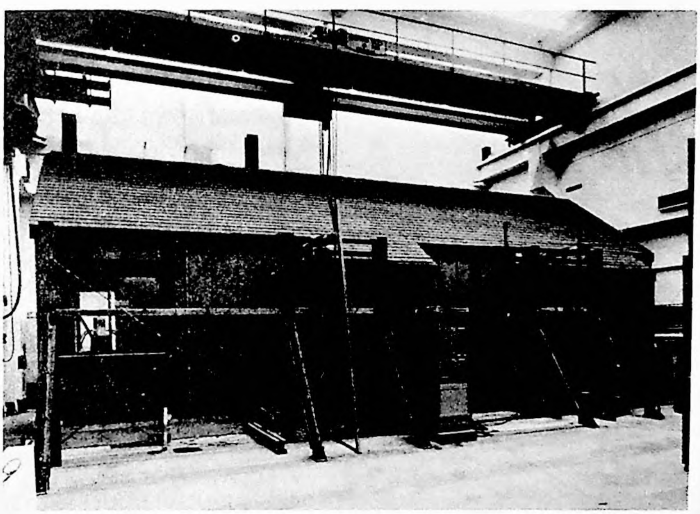

FIGURE 46
LABORATORY SET UP FOR APPLYING RACKING LOADS TO WOOD FRAMED MODULE

3.6.3 DUCTILITY TEST OF A CONCRETE FRAME [38]

In subsection 3.4.1 there was a discussion of tests made of column bearing details used in a precast concrete modular box system. As stated therein, the modules are stacked in a checkerboard fashion to form a multistory building. (See fig. 14.) Gravity and lateral loads are transmitted by the modules through monolithic beams and columns incorporated into each module. The modules are oriented transversely to the long axis of the building in a manner such that beam/column portal frames of modular width are located at each end of the module and along each side of the interior corridor. (See fig. 47.) This configuration results in four frames transverse to the long axis of each module. The transmission of horizontal forces through the length of the building is entirely through these frames.

Longitudinal wind load will not usually be a problem for a building of reasonable length, but the effects of seismic forces may be critical. The Guide Criteria recommend that:

> "The structure, when loaded with 1 dead load (1D), should not fail under 5 cycles of application of loads between the following limits:
>
> from +1E to −1E."

This means that the force carrying mechanism must be capable of sustaining severe reversals of loads and stresses. Since these stresses will probably be beyond the elastic range the frame must exhibit a degree of "ductility" which is the ability to undergo large inelastic deformations without failure. Unfortunately, this property cannot usually be determined by analysis.

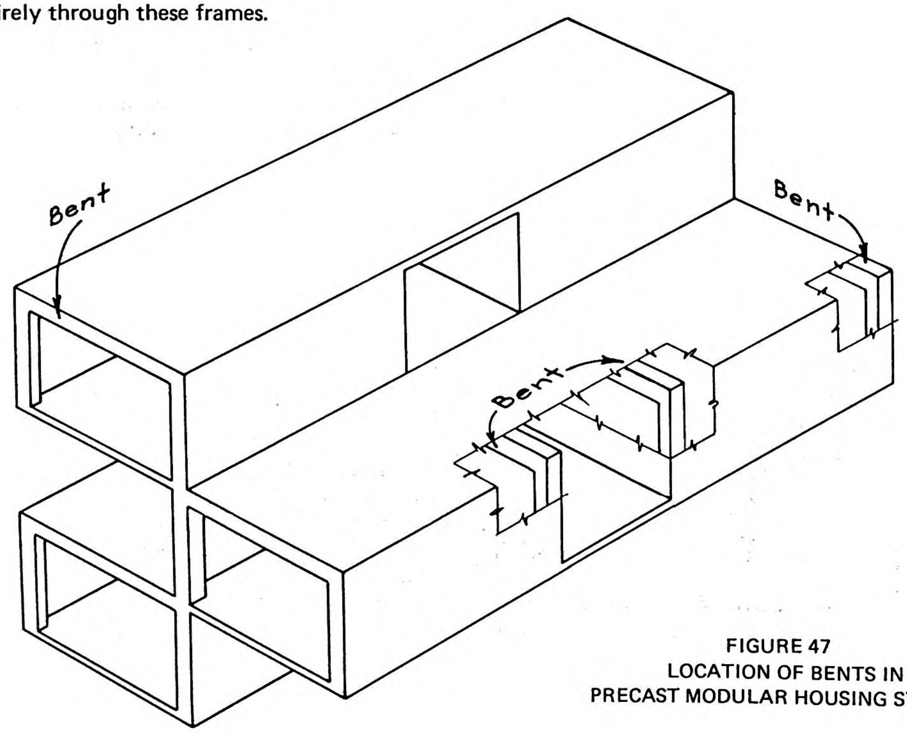

FIGURE 47
LOCATION OF BENTS IN
PRECAST MODULAR HOUSING SYSTEM

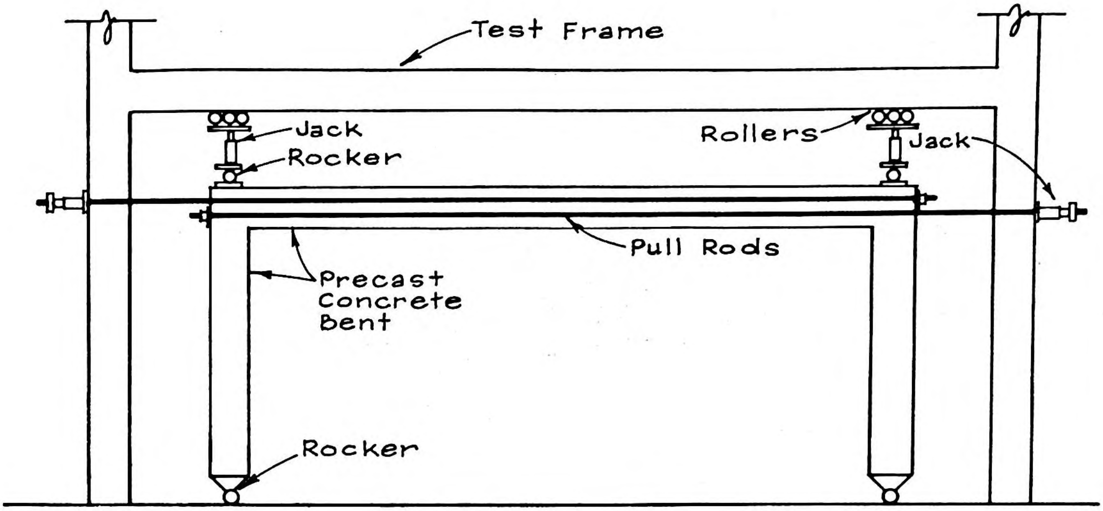

FIGURE 48
TEST SET UP FOR RACKING PRECAST CONCRETE BENT

These tests were intended to investigate the ability of the frames of this housing system to resist reversals of loading under the forces recommended in the Guide Criteria. It was also hoped that the work would be a guide in developing methods that could be used to investigate the same problem for other types of industrialized housing.

Two types of frames were tested. One was intended to represent a lower story frame with large vertical loads on the columns; the other, an upper story frame with small vertical loads on the columns. The test frames were lightweight concrete reinforced in accordance with the HSP's design. Loading was applied through the special setup shown in simplified form in figure 48. figure 49 is a photograph of an actual test.

Vertical loads were applied to the columns by hydraulic jacks and rockers with the jacks reacting against a steel frame through rollers. This arrangement for applying loads offered no horizontal resistance and the vertical load could be maintained even though the test specimen moved laterally.

Horizontal loading was applied through two more jacks (to apply the force in either direction) which pulled against the test frame through a loading yoke. Appropriate electronic devices were provided for measuring loads and displacements. The column bases rested on pins intended to simulate a hinge; this actually was a more severe condition than in the actual structure since there would have been some restraint from the pressure on the bearings and from the dowel crossing the joint.

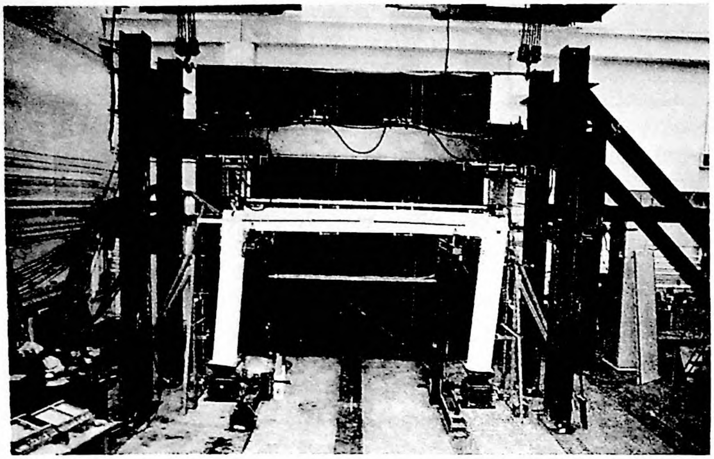

FIGURE 49
RACKING TEST OF PRECAST CONCRETE FRAME

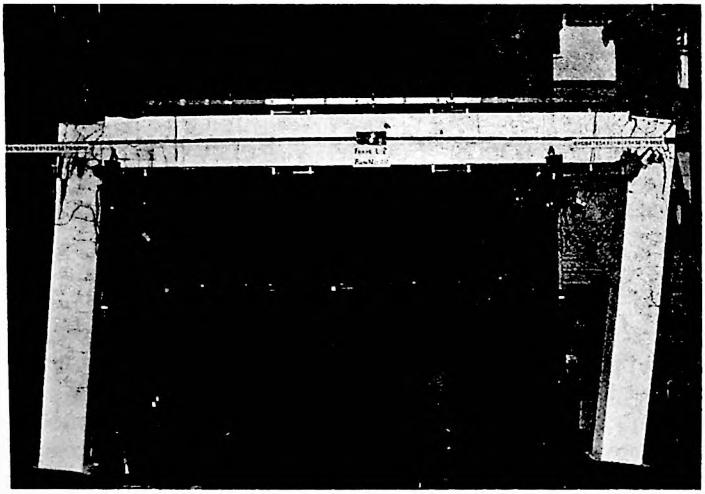

FIGURE 50
CONCRETE FRAME SHOWN IN FIG. 49 WITH COLLAPSE IMMINENT

The testing procedure was intended to experimentally determine the displacement (d) corresponding to the yield strength of the bent[1] and then apply two cycles of five times this displacement (5d), followed by three at 3/4 d and finally three more at 5d. The actual test procedure varied from this somewhat in that the load was not reversed during the last five cycles of the test of the lower story frame because of imminent collapse of the test assembly. One contributing factor was the large bending moments caused by the vertical loads as the frame deflected. (See fig. 50.) Another was due to the formation of a plastic hinge in the cross beam at a point where several of the negative moment reinforcing bars terminated. The upper story frame, with its smaller vertical load and different reinforcement details, withstood the planned cycles and, further, required

[1] A bent is two columns rigidly connected to the beam that they support; it has previously been described as a "beam/column portal frame."

an additional two cycles to deflect it to the limit of the testing equipment.

The results of these tests provided an indication of considerable ductility in the frames but the accompanying large lateral movement (sidesway) indicated that the effects of vertical loads are significant in the design and behavior of such frames. The tests also showed the need for careful detailing particularly with respect to reinforcement bar cutoffs to avoid weakening the structure. The ductility was determined in terms of deformation at yield rather than deformation caused by the specified seismic forces.

3.6.4 TESTS OF INNOVATIVE HOUSING COMPONENTS AND MODULE

The construction described in section 3.5.2 in connection with a panel test was a highly innovative Operation BREAKTHROUGH housing system. In the developmental stage, many investigations were made of the various elements by standard testing techniques.

One of these tests involved loading a "beam" which was a section of floor slab. This test provided helpful design information about load capacity, deflection, creep, and natural frequency, although the test specimen incorporated members not used in the final design.

Vibration tests were made on both a completed structure and an individual panel. A wall panel was tested in compression, as was a section cut from a module; these tests were repeated after storage under controlled conditions.

Tension and compression tests were made at different temperatures on the various materials incorporated in the panels. The plywood walking surface was tested with a concentrated load to check against the Guide Criteria. The shear strength of the paper honeycomb core and the strength of the bonding adhesive were tested, and a wall was loaded in conditions similar to those encountered in fire tests. Bearing tests were carried out on dry and wet gypsum board and tensile tests were made of a lapped fiberglass laminate joint.

The foregoing tests were made primarily to obtain knowledge of working stresses for the various components. Later, when the final design was completed, a full scale module was manufactured and tested after being transported from the factory to a building site where it was erected on a prepared foundation.

The first test conducted on the completed module was the application of a force intended to simulate an ultimate wind load of 1.3 times the design value. Loads were applied with jacks pushing at the upper corners of the long side and reacting against steel frames held by sandbags.

Jacking forces and lateral deflections were observed. The bottom of the module was restrained on the side opposite the jacks so that it would not move; after the test load was released, the restraints were removed and a lateral force was applied to the module to note the force required to move it on its foundation.

A second test consisted of applying uniform loads (sandbags) to the floor and ceiling assemblies for 24 hours. Deflections were measured at the beginning of the 24 hour period, at the end of the 24 hour period, and after removal of the load (residual deflection).

In the third test, intended to simulate the foundation settlement conditions recommended in the Guide Criteria, one side of the module was raised above the other and a load of 1.4D + 1.7L was placed on the floor, with deflections noted during loading and after removing the loads.

A floor loading of 1.3 times the specified value of 1.4D + 1.7L was next placed on the floor with deflections being measured. Some evidence of distress was noted, and when the loads were removed, a portion of the floor was removed for examination. After this, the floor was reloaded until failure occurred.

3.6.5 TRANSPORTATION AND ERECTION OF AN INNOVATIVE HOUSING MODULE [39]

Transportation is a necessary consideration in the development of any housing system. Not only are the logistics of moving a large (and often oversize in terms of shipping limitations) prefabricated unit substantial but the problem of damage while loading, transporting, and erecting a module may also be critical. This is compounded where an innovative construction is concerned particularly if it involves materials that may be rather fragile.

When the manufacturer whose test work was described in section 3.6.4 shipped the specimen module, he arranged to have the process from factory shipment to setting it on the prepared foundation monitored by technical observers. Moving and erecting the module were routine affairs with no damage occurring during transportation. However, because of a somewhat unstable lifting rig, one corner of the module struck the ground causing some minor cracking.

In order to study the effect of rough roads on the unit a "bump course" consisting of a series of boards was placed on the roadway and the trailer, with the module aboard, was driven over it at speeds up to five mph. No damage was caused although it was estimated that the acceleration force was 1.75g. Further, it was estimated that a speed of ten mph over the same "bump course" might cause damage.

On the basis of this test, it was recommended that the lifting system be modified and that a "bump course" test be required for all modular housing systems to determine their susceptibility to damage during transportation.

3.6.6 FLOOR VIBRATION TESTS ON COMPLETED UNITS AT A BREAKTHROUGH SITE [40]

After several of the housing units at the Kalamazoo, Michigan, BREAKTHROUGH site had been completed and furnished, vertical displacement measurement tests were carried out on three different types of floor systems to determine their vibrational characteristics. The three floor constructions were:

1. Wood joists and plywood subfloor.[1]
2. Light gage steel joists and plywood subfloor.
3. Light gage steel joists with paper honeycomb floor panels.[2]

The testing was done at the job site with equipment and methods used for similar

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[1] This is part of the system described in section 3.6.2.

[2] This is part of the system described in section 3.5.4

testing performed in the laboratory at NBS. A weight was dropped from a measured height and displacements with respect to a fixed beam spanning the room in which the test took place were measured by electronic equipment. Tests were made in both the bedroom and living room areas of one and two story attached and detached buildings.

Test results were not conclusive, but they did indicate differences in stiffness between different rooms in the same housing unit and among the various floor types. In general, the paper honeycomb panel with steel joists appeared to be the stiffest, while the steel joist and plywood floor was least stiff. Estimated damping was between 7 percent and 13 percent. Vibrations ceased within 0.45 sec for all rooms and all flooring systems.

It was not intended that this test be an attempt to evaluate the three systems of building construction with respect to the Guide Criteria, although such data as are presented indicate that the Criteria recomendations were met.

3.6.7 STRUCTURAL TESTS OF INNOVATIVE HOUSING MODULE AND ITS COMPONENTS [41]

The construction described in section 3.3.2 was an important element in one of the Operation BREAKTHROUGH building systems where the fiberglass reinforced polyester sandwich panels were used for walls, roofs, and interior partitions. These were joined with floor panels constructed of wood joists and plywood to form modules which were shipped from the factory to be job assembled into completed dwelling units. The latter were generally placed side by side in groups.

In order to evaluate the behavior of the system with respect to the recommendations of the Guide Criteria, two modules were assembled on a foundation in a test laboratory and subjected to a series of nine tests. Three of these dealt with structural serviceability, viz:

1. Four cycles of lateral load increasing to the Criteria recommendation of 0.9D + 1.0W.
2. Two cycles of increasing vertical load to a level of 1.0D + 1.0L.
3. One cycle of combined vertical and lateral load to a level of 1.0D + 1.0L + 1.0W.

The other six tests, dealing with structural safety, were:

4. One cycle of vertical load equivalent to 1.2D + 1.5L and maintained for 24 hours.
5. One cycle of increasing load to a level of 1.4D + 1.7L.
6. One cycle of increasing vertical and lateral loads to a level of 1.1D + 1.3L + 1.3W.
7. Two cycles of vertical load and reversing seismic load at levels of 0.9D ± 1.45E.
8. Two cycles of vertical and reversing seismic load at levels of 1.1D + 1.3L ± 1.45E.
9. Three cycles of increasing vertical and lateral load to a level of 0.9D + 1.3W, with a fourth cycle in which the lateral load was increased until racking failure took place.

Vertical loading was obtained by ponding water on the floors and roof; lateral forces (simulating both wind and earthquake loadings) were effected by line loads applied at the second floor and roof lines by hydraulic jacks reacting against a heavy steel beam. (See fig. 51.) Dial gages were used to measure horizontal and vertical deflections. Results of the tests indicated that the single two story module complied with the recommendations of the Guide Criteria for live, dead, and earthquake loads. However, drift under design wind loads was excessive and the ultimate wind load capacity was inadequate. Tests at extreme wind loads revealed weakness in details that required correction. Since these modules are intended for single family attached houses, sometimes referred to as "town houses" or "row houses," it was recommended that a minimum of three attached units be utilized to provide adequate lateral strength.

In addition to the tests listed above on a two story housing unit, other investigations were made to study the behavior of certain shear walls. A specially designed one story module was used for this purpose. It consisted of floor, roof, and side wall panels. The end panels extended only about half way across the module, and provided the shear resistance of the unit. A lateral line load was applied at the roof line by hydraulic jacks reacting against a steel beam. Three cycles of loading representing service wind load were applied. Next the module was loaded until a failure in the attachment to the foundation caused some damage to the module; it was repaired, the foundation detail was reinforced, and the foundation connection strengthened. After this the racking force was applied again until failure occurred. Results of the test indicated that the module meets the Criteria recommendations for structural serviceability and safety under wind load if used as a one story house, but not when used as the lower element of a two story building. In the latter case, as stated above, it would be necessary to have three houses in a row.

In order to study the effect of moisture and temperature on the panels, certain specimens were conditioned at high humidity (99% relative humidity) and temperature [71°C (160°F)] for 235 hours. In the case of roof panels one conditioned and one nonconditioned sample were loaded in an inverted position by an airbag. Both specimens complied with the Criteria recommendations for serviceability and strength, and there was no measurable effect due to the conditioning process.

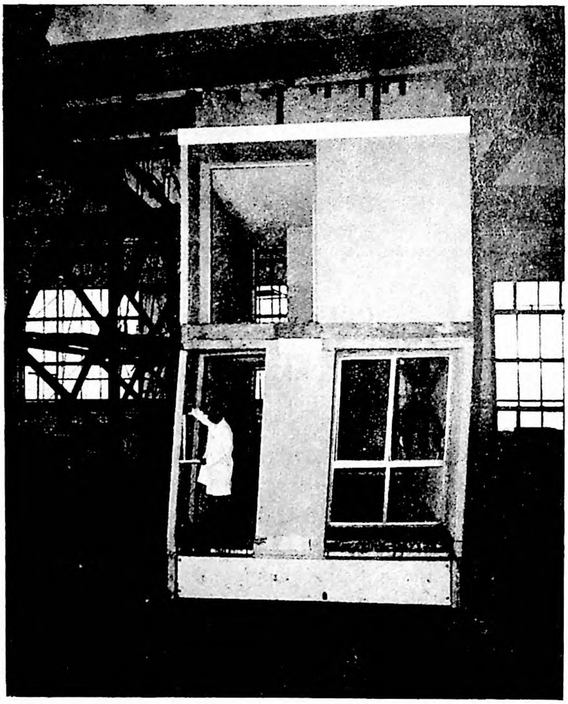

FIGURE 51
APPLYING LATERAL LOADS
TO A TWO STORY MODULE

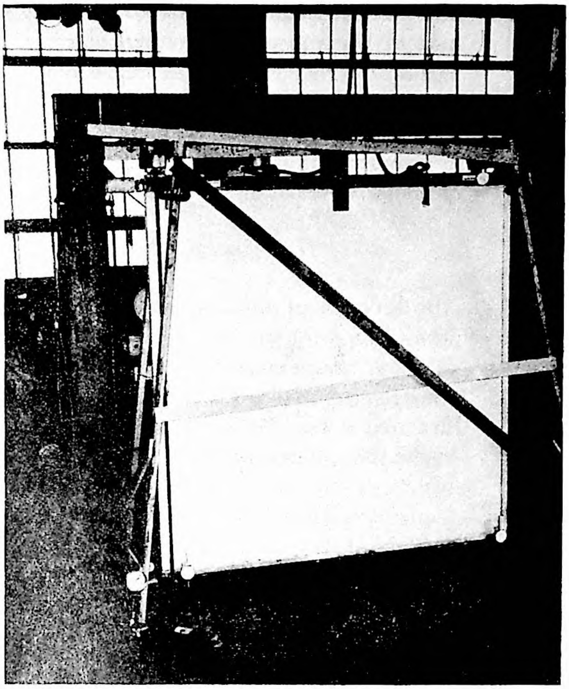

FIGURE 52
RACKING A PANEL USED IN
THE MODULES SHOWN IN FIG. 51

FIGURE 53
LONG TERM TEST
OF ADHESIVE USED IN
MODULES SHOWN IN FIG. 51

A conditioned panel was subjected to a compression test, and it was intended to compare the results of this test with those obtained with a nonconditioned panel tested in another laboratory. However, faulty fabrication led to premature failure and this could not be done.

The racking strength of both conditioned and nonconditioned panels was determined by testing carried out in accordance with the procedures of ASTM E 72. In order to better represent the condition in an actual house, each panel included a joint. Loading was done with a hydraulic ram reacting against a steel frame. Tie rods were placed near the edges of the panel to simulate the effect of an adjoining panel. Deflections were measured by dial gages. (See fig. 52.) Three nonconditioned and one conditioned panel were tested. The results of this test indicated that the panel has adequate racking strength if the sill is properly secured to the floor system. Unfortunately, again due to a manufacturing defect, it was impossible to gain an exact knowledge as to the strength of the conditioned panel, but it was as strong as one of the nonconditioned panels.

The last series of tests was made to investigate short and long term strength. Specimens were made by bonding two of the polyester shells to two pieces of lumber to form a hollow box. Test loads were applied by pulling against the wood members, thus putting the joints in shear. Short term loads were performed in a testing machine at room temperature and humidity; the specimens had been conditioned at 35°C (95°F) and 90% relative humidity for three days, in most cases. The long term or creep tests were made by suspending weights from the specimens. (See fig. 53.)

4

miscellaneous tests

4.1 ACOUSTIC TESTS

4.1.1 NOISE SURVEY OF A PROTOTYPE SITE

The Jersey City Operation BREAK-THROUGH site, located in a busy city center, is representative of many densely populated urban areas. This test program was carried out "to provide a quantitative analysis of the existing acoustical environment at the site," and to compare observed data with established HUD guidelines. [42]

Hand held meters were used to measure sound levels at 28 locations and approximate sound level contours determined. On the basis of this information and a plan of the building site, seven data stations were selected for further investigation. One of them was near a proposed "total energy" plant planned for the project. Sound at the stations was collected by microphones and recorded on magnetic tape at intervals over a period of four days. At the same time, traffic counts were made with equipment set up by the local police department and aircraft overflights noted visually.

Data were analyzed by computers and the A-weighted sound levels[1] determined. These were then subjected to the "screening" described in Reference 44 and the results compared with established criteria.

The results of these tests were of value to the housing system producers in determining noise shielding requirements.

[1] This weighting procedure attenuates sound measurements to reflect the frequency response of the human ear.

4.1.2 ACOUSTICS OF SINGLE EXTERIOR WALL AND DOUBLE INTERDWELLING WALL OF INNOVATIVE MATERIALS

The acoustic properties of wall assemblies of conventional materials can be calculated from the known physical properties of their components. When innovative materials with unknown physical properties are employed it is necessary to establish values experimentally. Similarly unusual designs, such as the double leaf walls frequently found where factory built modules adjoin, require testing. These tests were made to determine the sound transmission class (STC) of several innovative panels intended for use in single and double walls.

The walls in the housing system described in section 3.3.2 and illustrated in figure 13 were made of two flat sheets of fiberglass reinforced polyester laminate separated by a corrugated sheet of the same material glued to the flat sheets. Voids in the panels were filled with mineral wool insulation. Two tests were made, one of a single wall and the other of a double wall with a 1-1/2 inch air space between the panels. In the latter case the exterior faces were covered with 5/8 inch gypsum wallboard.

Tests were conducted in accordance with ASTM E 90 [43] and ASTM E 413 [44] with measurements of sound transmission loss through the specimen made over a prescribed band of frequencies. Sound transmission classes were then computed in accordance with the cited ASTM standards, and these values used to determine compliance with the Guide Criteria.

Another innovative wall assembly, described in section 3.5.2, consisted of gypsum board bonded through a woven fiberglass mat to each side of a paper honeycomb. The weather (exterior) face was covered with a fiberglass mat bonded to the gypsum board. Three assemblies were tested to measure the sound transmission loss and hence the degree of protection against airborne noise. One was a wall constructed as described above. The second was a double wall with two panels of the same type separated by a 2 inch air space, and the third was a similar double wall with a ½ inch sound attenuation blanket in the 2 inch air space. (See fig. 54.)

Testing was in accordance with ASTM E 336 [45] with measurements made of the intensity of a standard noise source transmitted through the assembly. The data obtained were used to calculate sound transmission classes to compare with the recommendations of the Guide Criteria.

4.1.3 ACOUSTIC TESTS OF TYPICAL FLOOR/CEILING ASSEMBLIES

A number of multistory Operation BREAKTHROUGH housing designs incorporated floor/ceiling constructions in which a module, whose base consisted of a floor assembly complete with joists, was installed above the ceiling assembly (including joists) of another module. (See fig. 55.) This program was undertaken to study the acoustic properties of a typical arrangement having this configuration and also to determine the changes in acoustic properties that would occur when a floor covering is added.

The floor assembly consisted of plywood subflooring supported on wood joists; the separate ceiling assembly was composed of gypsum board installed on the underside of wood ceiling joists, with fiberglass insulation between the joists. Two test specimens, one without a floor covering, and the second with a foam backed vinyl glued to the plywood subfloor were tested. In the first type of test, which was intended to determine the transmission of impact noise, a tapping machine was operated at four different locations on the floor and measurements were made in accordance with International Standards Organization (ISO) R 140 [46] modified for American practice. In the second type of test, the transmission loss of airborne sound was checked by ASTM E 90.

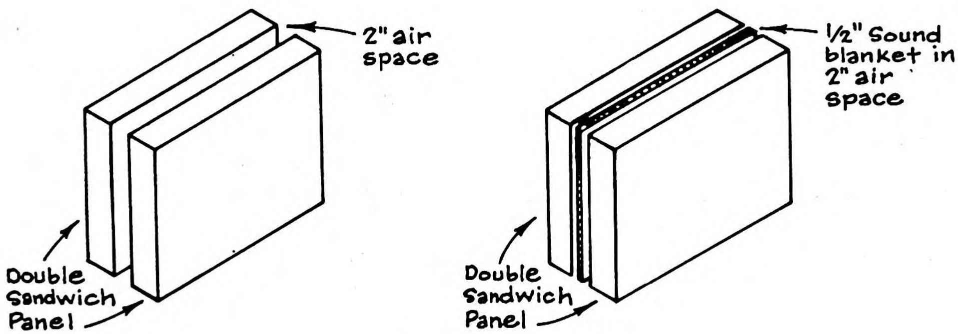

FIGURE 54
DOUBLE SANDWICH PANEL PARTITIONS USED IN ACOUSTIC TESTS

The impact insulation class (IIC) and sound transmission class (STC) were calculated in accordance with procedures established by References 44 and 46, respectively.

Computations indicated that the STC was not changed by the floor covering although the IIC was increased nearly 20 percent. These values were then compared with the recommendations of the Guide Criteria.

4.1.4 ACOUSTIC EVALUATION OF COMPLETED MODULAR HOUSES [47], [48], [49], [50]

Although an engineering review of submitted plans and specifications was the primary basis for determining the acoustic acceptance of Operation BREAK-THROUGH housing systems, it was recognized that construction details which

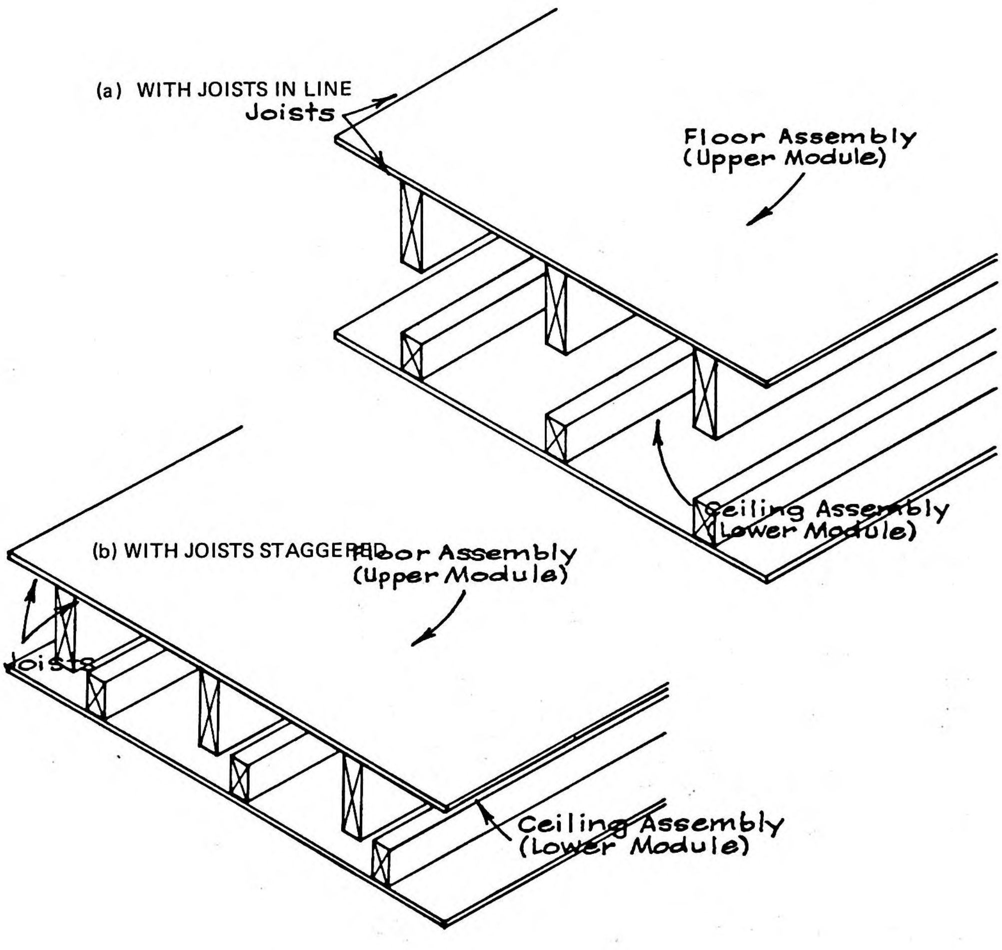

FIGURE 55
FLOOR/CEILING ASSEMBLY WITH ONE MODULE PLACED ABOVE ANOTHER

did not lend themselves to analysis could have a significant effect on actual acoustic performance. For this reason a series of field studies was undertaken to measure inter-dwelling and intra-dwelling noise isolation in several Operational BREAKTHROUGH housing systems and to assemble data that would be useful in making a comparison with conventional housing. An on-site mobile acoustical laboratory was used to make impact and sound transmission measurements in accordance with the procedures given in ASTM E 336, ASTM E 413, ASTM RM 14-4 [51], ASTM C 423 [52], and American Standards Institute (ANSI) S1.2. [53]. (See fig. 56.)

Several types of housing units were studied including: single family and multifamily, attached and detached, one story and low rise. The housing designs included construction such as wood flooring on steel joists and steel faced paper honeycomb core sandwich panels. Measurements were made between several different room combinations for inter-dwelling and intra-dwelling walls, including single and double wall assemblies, and floor/ceiling assemblies. The effects of noise caused by heaters and garbage disposers were also studied.

As a result of the testing, noise insulation class (NIC) and impact insulation class (IIC) values were computed and compared with the values recommended in the Guide Criteria.

4.2 PLUMBING TESTS

Only one Operation BREAKTHROUGH test dealt directly with an innovative plumbing system. However, it was of considerable interest since it involved a design feature that represented a departure from usual American practice and was not in compliance with most American plumbing codes.

FIGURE 56
MOBILE ACOUSTIC
TEST LABORATORY

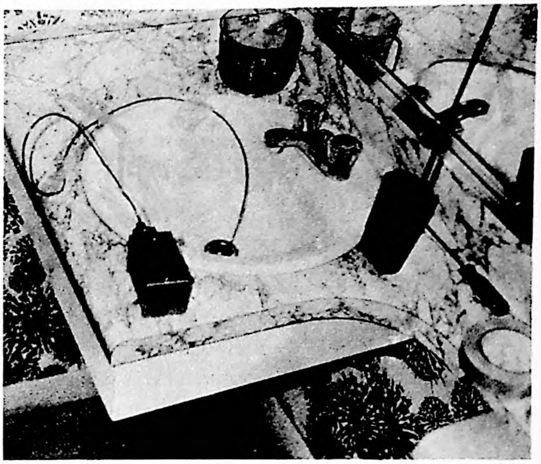

FIGURE 57
TESTING FLOW IN A SINGLE STACK DWV SYSTEM. LEFT, MAKING MEASUREMENTS OF TRAP SEAL DEPTH IN A KITCHEN SINK USING A PNEUMATIC TECHNIQUE; ELECTRONIC MEASUREMENTS COULD NOT BE USED BECAUSE OF A FOOD DISPOSER. RIGHT, USING AN ELECTRONIC TRAP SEAL LEVEL DETECTOR. BOTH METHODS ARE NON-DESTRUCTIVE.

4.2.1 FIELD TESTS OF A SINGLE STACK DRAINAGE SYSTEM [54]

Single stack DWV[1] systems similar to those used by one of the HSPs at the King County, Washington, Operation BREAKTHROUGH prototype site have been used to a considerable extent in Great Britain but have not been generally used in this country.

Hydraulic test loads were selected that involved one or more fixtures (water closets, lavatories, kitchen sinks, and/or bathtubs) on the basis of both British and American experience in hydraulic testing. Various combinations of hydraulic loads that might be discharged simultaneously were utilized in testing the performance of the DWV system. The various fixtures were either filled or partially filled to representative amounts and discharged into the DWV system, at which time measurements and observations were made.

Performance characteristics that were investigated included:

1. Trap seal retention in idle fixtures.
2. Resistance to ejection of suds, sewage, or gas (blow back).
3. Cross flow.
4. Self siphonage.

In several cases substances (detergent, paper diapers, etc.) were added to the clean water in order to better represent the more severe conditions that would occur in actual operation.

Trap seal retention and self siphonage were measured visually with vertical scales in water closets, by a pneumatic pressure vacuum gage assembly in kitchen sink traps, and by an electric probe in bathtubs, lavatories, laundry sinks, floor drains, and washing machine standpipes. The electric probe technique was specially developed for use in this project. (See fig. 57).

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[1] Drainage, waste, and vent

Blow back was detected visually and audibly while cross flow was detected by the visual observation of a dye placed in the trap seal of an active fixture and sampled (after the test) in the trap seal of an adjacent idle fixture.

The tests indicated that the single stack DWV system complied with the Guide Criteria with the exception of cross flow. It was additionally concluded that the small amount of cross flow observed was due to faulty installation of the branch piping.

4.3 ELECTRICAL TESTS

4.3.1 LABORATORY PERFORMANCE TESTS ON SWITCHES AND RECEPTACLES FOR PREFABRICATED MODULAR HOME WIRING HARNESSES AND OTHER RESIDENTIAL WIRING SYSTEMS

One Operation BREAKTHROUGH HSP proposed to use electric wiring devices (switches and receptacles) for which approval by nationally recognized testing agencies had not been obtained. These tests were made to determine the compliance of the devices with standards which are generally referenced in electrical codes. Testing was carried out primarily in accordance with appropriate portions of the following UL[1] standards:

UL 20–1970 Revision, "Snap Switches" [55]

UL 498–1970 Revision, "Attachment Plugs and Receptacles" [56]

UL 514–1970 Revision "Outlet Boxes and Fittings" [57].

[1] Underwriters' Laboratories

Several additional non-standard tests were made in order to establish a basis of comparison with currently accepted devices.

The sixteen separate tests which follow were carried out:

1. *Dielectric Withstand.* This determines if the devices can withstand without breakdown a 60 hertz potential of 1,500 volts applied for one minute between live metal parts of opposite polarity and between live and dead metal parts. In addition, a test not required by UL was performed—determining the voltage at which dielectric breakdown occurred.
2. *Retention of Caps* (Receptacles Only). This determines the force required to withdraw two prong and three prong caps from an outlet device both before and after overload and temperature tests. This force is required to be between 3 and 15 lb.
3. *Overload Capacity.* Switches must pass a test consisting of 100 cycles of operation at 4.8 times the rated current. These tests should not cause mechanical or electrical failure, undue wear, or burning and pitting of the contacts.
4. *Endurance* (Switches Only). Subjecting switches to 30,000 cycles of operation—10,000 for each of three different loads—should not cause mechanical or electrical damage, burning or pitting of contacts, or loosening or wearing of parts that would impair their normal operation.

5. *Temperature Rise.* This test measures the temperature rise at the wiring terminals of electrical devices; it must not exceed 30°C (54°F) after four hours of carrying its rated current.

6. *Limited Short Circuit Test* (Switches Only). This tests the ability of a switch mounted in a metal enclosure to carry a heavy short circuit current (3,500 amperes) without igniting either cotton packed around all openings in the enclosure or the insulation on the conducting wire. In addition, there must be no emission of flame or molten metal (mercury excepted) from the enclosure.

7. *Resistance to Arcing* (Receptacles Only). This test is required if a material other than phenolic, urea, melamine, or cold molded composition is used in the construction of a cord connector body or current tap in such a way that the material is likely to be exposed to arcing while in service. It is carried out by applying 200 cycles of additional operation under the overload capacity test conditions to the receptacles that have previously been subjected to 50 overload cycles and the temperature and cap withdrawal tests. Neither electrical or mechanical failure, nor pitting and burning of the contacts should occur.

8. *Potential Drop in Grounding Connections.* (Switches are not covered in UL standards, but this test was performed on both switches and receptacles.) This test determines the drop in potential from the grounding contact or blade to the grounding terminal while a direct current equal to the maximum rated capacity of the device is passing. This drop must not exceed 30 millivolts.

9. *Continued Endurance* (Switches). After completion of the previous tests, the switches must be capable of operating through 15,000 cycles without impairment of their normal function.

10. *Effect of Heat on Switch Actuator.* After being heated to 65°C (149°F) for an hour, the switch is immediately operated through 25 cycles with a force of ten lb on the actuator. The actuating member should not be affected adversely to the extent that it is appreciably deformed or fails to operate the mechanism during the 25 cycles.

11. *Cable Clamping Strength.* This test measures the ability of an electrical cable clamp or connector to withstand a pull on the cable without damage or significant movement or loosening of the cable. For nonmetallic sheathed cable, a direct pull of 60 lb is applied for five minutes between the cable and the box in which the clamp or connector is mounted.

12. *Insulation Resistance* (Both switches and receptacles were subjected to the test, although the UL standard only refers to receptacles.) This test measures the resistance of the insulation to the passage of current between live metal parts of opposite

polarity, live metal parts and dead metal parts exposed to contact by persons or that may be grounded in service, and live metal parts and insulating materials exposed to contact by persons or that may be grounded in service. The insulation resistance must exceed 100 megohms.

13. *Case Crush Resistance.* (This test is not in the UL standards, but was conducted to obtain design information.) The test measures the ability of a case when placed between two flat blocks to resist a force of 75 lb, applied for five minutes, without damage.

14. *Mounting Strength.* This test, conducted in accordance with Paragraph 109 of UL Standard 514, determines the ability of an installed device, when securely attached to a standard mounting board, to resist a double acting force of 50 lb applied along the centerlines of all three axes. Failure criteria include "breakage or separation of the device body, or any other evidence of mechanical or electrical hazard." Both switches and receptacles were evaluated.

15. *Impact.* (This test is not specified in the UL standards, but was conducted to obtain engineering design information.) The tests determined the amount of damage that occurred when the innovative electrical devices were struck by a five lb steel weight dropped from various heights.

16. *Flame Resistance.* This test method determines the self extinguishing nature of the case materials, which must not burn for more than one minute after five 15 second applications of a standard flame.

As a result of these tests it was judged that the devices should be suitable. This was important because of the general recommendation that all innovative electrical devices used in Operation BREAKTHROUGH be safe, functional, and durable.

4.4 IMPACT OF PROJECTILES (HAIL) ON ROOFS AND SIDING

Each year there is a large monetary loss in the United States caused by hailstorms. This makes it important that any exterior surface be capable of sustaining an impact from wind driven hail without damage. In order to deal with this problem, the Guide Criteria contained a provision (based on experience with asphalt roofing) recommending that the roofing membrane be able to resist hail impact. The provision initially recommended resistance to a 1½ in diameter hailstone traveling 112 fps[1] without breaking or cracking; this was later changed to 1¼ in and 82 fps based on an extensive experimental program on asphalt shingles.

4.4.1 TESTS OF ROOFING MEMBRANES

Since there was no information available as to the hail impact resistance of the fiberglass reinforced polyester and the steel faced paper honeycomb sandwich

[1] fps = feet per second

panel roof systems described in sections 3.3.2 and 3.5.4 respectively, it had to be determined experimentally.

The test procedure utilized a "hail gun," (See fig. 58) which shot ice spheres, of 1½ in diameter and weighing approximately 0.92 oz, at the exposed roofing surfaces at an angle of 90° and a velocity of approximately 112 fps. Thirteen test spheres were used in one case and five in the other. In the case of the roof panel consisting of fiberglass reinforced polyester, there was no substantial indentation, but for the steel faced honeycomb panel the indentations were sizeable. However, in neither case was the surface broken, and, therefore, both panel systems complied with the applicable provision of the Guide Criteria.

4.4.2 TESTS OF SIDING

The fiberglass reinforced polyester panels whose testing as a roofing material has been described in the preceding section also served as siding when the panels were used for walls. Their impact resistance in this situation was evaluated somewhat differently. Testing was carried out with the hail gun, which shot spheres ranging in size from 1¼ in to 2 in diameter, and weighing from 0.53 oz to 2.3 oz, with speeds of 84 fps to 124 fps at the wall surface. Because this material was intended for use as siding rather than roofing, it was felt that an impact angle of 45° to the surface represented more nearly actual exposure conditions than did 90°. For purposes of comparison, both angles were used in the tests. In six out of 15 cases some cracking took place, but in all of these cases the velocity was higher than that recommended by the Guide Criteria. Some of the indentations were rather large; however, no cracking was observed when the velocity was below the value of 82 fps mentioned in the Guide Criteria.

4.5 DURABILITY OF AND PERMEABILITY OF PAINTS, COATINGS, AND SURFACES

4.5.1 TESTS OF PAINTS AND COATINGS

Paints and coatings proposed for use by several Operation BREAKTHROUGH HSPs were tested to evaluate their serviceability. Each covering was subjected to a number of the tests listed below in order to determine their properties. Most of the testing was by methods described in Federal Test Method Standard 141a. [58] Procedures referred to hereinafter are those given in this standard.

1. Adhesion
2. Flexibility
3. Color and Gloss Retention
4. Resistance to Chalking, Cracking, and Crazing
5. Embrittlement
6. Hiding Power
7. Resistance to Wind Driven Rain
8. Impact Resistance
9. Washability
10. Scrubability
11. Mar Resistance

Adhesion was measured by the "parallel groove" method which determines how closely a series of parallel grooves can be

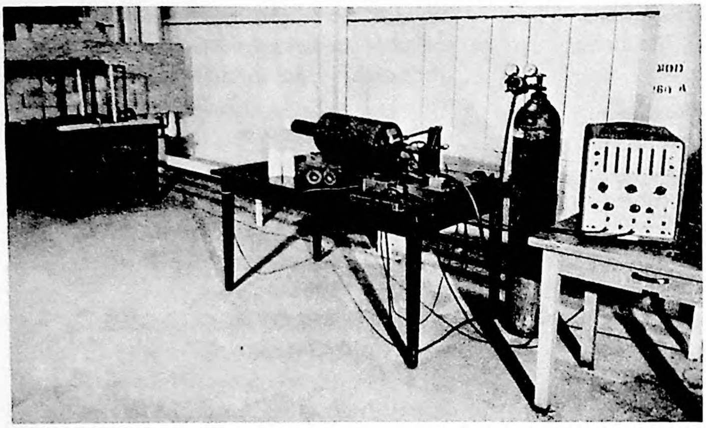

FIGURE 58
HAIL GUN

cut through a coated surface without lifting or tearing the coating. The better the adhesion, the closer the grooves can be cut before failure. Procedure 6302.1 [59] was used for this test.

Flexibility was determined by bending coated metal test panels around a series of steel rod mandrels of different diameters and finding the smallest diameter mandrel which did not cause the coating to crack. This followed Procedure 6221. [60]

Color and gloss retention was checked by measuring changes in color and gloss that occurred as a result of exposure to an arc light for 1,000 hours with 18 minutes of water spray every two hours. Procedure 6152 [61] applied to the exposure cycle; colored paints were judged by Procedure 6123 [62] ; gloss paints by Procedure 6104 [63] ; and flat paints by Procedure 6103. [64] Resistance to chalking, crazing, and cracking was assessed by making visual observations on the exposed color and gloss specimens. Similarly, the test for embrittlement was made by conducting the flexibility test on specimens that had been exposed in the same way.

Hiding power or opacity—the ability to cover underlying darker colors—was determined by applying a controlled amount of coating on a substrate covered with alternating black and white markings and then computing the contrast ratio for the film. The contrast ratio is calculated by dividing the reflectance measured over the black portion of the substrate by the reflectance measured over the white portion. This was done by Procedure 4122.1. [65]

The provisions of Federal Specification TT-C-00555 [66] were used to investigate the resistance of a coating to wind driven rain. The test consisted of subjecting the coating applied on a masonry substrate to a water spray, which simulated rain driven by a 98 mph wind, and measuring the amount of water penetration.

The impact resistance test provided a measure of the ability of a coating to maintain its integrity when the film and the surface on which it is applied are distended beyond their original form by impact. In this test a coated metal panel is struck by an impacter (see fig. 59) and the

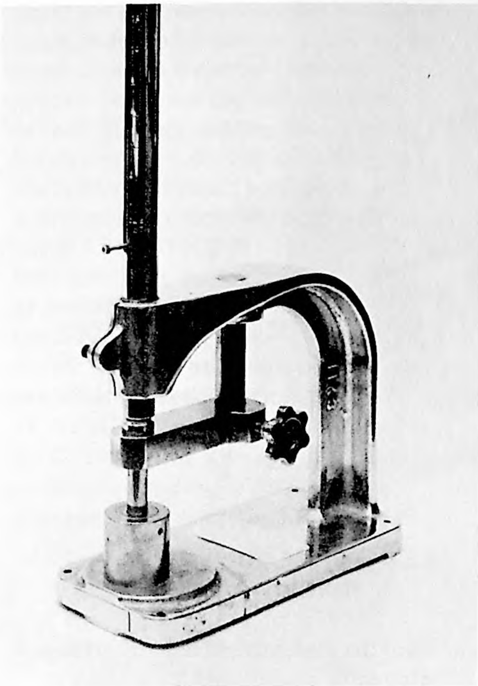

FIGURE 59
PAINT IMPACT TESTER

highest area of distensibility in which there are no film breaks is reported as percent elongation. This followed Procedure 6226. [67]

The washability of paints was determined by subjecting a soiled specimen which was previously painted to the cleaning action of a wet sponge and cake grit soap in an apparatus which imparts a reciprocating motion to the sponge across the length of the painted test specimen. (See fig. 60.) Reflectance and gloss measurements made on the coated specimen both before and after washing provided an indication of both the degree of soil removal and of changes in gloss brought about by the cleaning process. Procedure 6141 [68] applied to this test.

Scrubability, which was tested by Procedure 6142 [69] in the same basic apparatus, subjected the coating to the abrasive action of a bristle brush wetted with soap solution. In this test, visual observations are made of the film wear which occurs after a specified number of test cycles.

Mar resistance was examined by marking the coated surface with pencil and felt tip markers and soiling it with food stains prior to subjecting the surface to the washability test mentioned above and observing the degree of soil removal obtained. Visual observation was used to judge the suitability of the coating.

4.5.2 TESTING OF A FIBERGLASS REINFORCED POLYESTER PANEL SYSTEM

The Operation BREAKTHROUGH system described in section 3.3.2 used an innovative structural system for both exterior walls and roofing panels. Since there was not sufficient information available to predict the durability of the system, several tests were conducted.

First, a preliminary screening test was carried out in which coupon specimens of the paneling were exposed to a series of aging cycles for 1,000 hours in a twin arc Weather-O-Meter. Each aging cycle consisted of 1 hour, 42 minutes of light followed by 18 minutes of combined light and water spray. At the end of the test period, only slight darkening of the test specimens could be observed, with no apparent surface damage, thus indicating that the material was probably satisfactory. Later, a more extensive investigation was carried out.

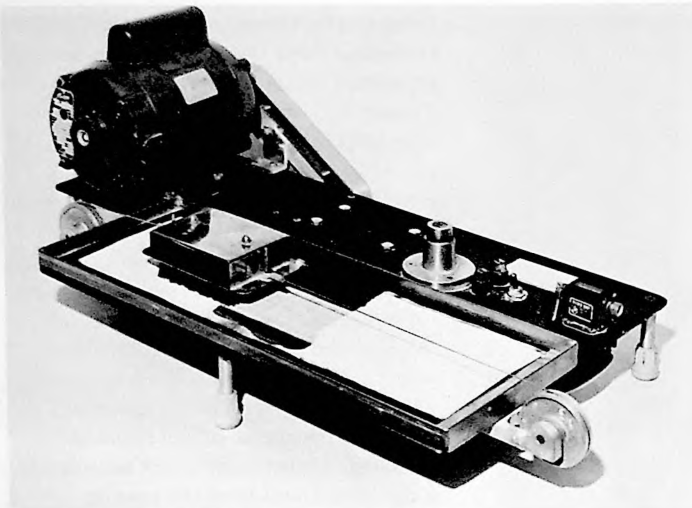

FIGURE 60
PAINT WASHABILITY TESTER

Several of the test procedures discussed in section 4.5.1 were used for this more detailed study. Resistance to wind driven rain was determined in accordance with Federal Specification TT-C-00555 in which water, under a pressure corresponding to a 98 mph wind, was sprayed on the specimen for 72 hours. The effects of accelerated weathering on color retention, gloss retention, and the adhesion of aggregate particles on the surface of the walls were assessed by exposing the specimens in the Weather-O-Meter, as mentioned previously, and using measurements of light index and gloss before and after exposure plus visual inspection as evaluative tools.

Washability and scrubability were determined by testing specimens for 100 cycles with grit soap and a sponge and for 1,000 cycles with a bristle brush and soap solution, respectively. Mar resistance was evaluated by marking the surface with a pencil and felt tip marker, staining it with several food items, and then scrubbing the surface with grit soap and visually inspecting the results.

4.5.3 PERMEABILITY OF INNOVATIVE SURFACES

Since the innovative fiberglass surfaces referred to in sections 3.3.2 and 3.5.2 formed part of the exterior membranes in their respective housing systems, it was necessary that they provide the resistance to moisture penetration recommended by Guide Criteria. The "dry cup method" of ASTM Method E 96 [70] was used to measure their water vapor permeability under standard conditions and hence indicate their performance.

The results of this test showed that both materials were acceptable and that they had such low vapor transmission values that they could be classified as having zero permeability.

4.5.4 LABORATORY AGING OF SANDWICH PANELS

The housing design for Operation BREAKTHROUGH referred to in section 3.5.2 used composite exterior panels consisting of plywood (on the interior) bonded through a woven mat of fiberglass to a paper honeycomb core. On the other (exterior) side, gypsum board was applied onto a sheet of resin impregnated fiberglass mat bonded to the core. The durability of the system was tested by exposing a specimen to six complete cycles of Cycle A of ASTM C 481 [71] and then inspecting the specimen for signs of deterioration. Each complete cycle of Cycle A consists of soaking in water for 1 hour followed by spraying with steam and water vapor for 3 hours, storing at 12°C (54°F) for 20 hours, heating at 99°C (210°F) for 3 hours, spraying with steam and water vapor for 3 hours, and then heating in dry air at 99°C (210°F).

4.6 OTHER TESTS

4.6.1 TESTS OF SEALANTS

Failure of the butyl rubber tape sealant used between the steel faced sandwich panels discussed in section 3.5.4 would impair the weathertightness of the system. The three tests whose descriptions follow were conducted to ensure that the taping system would provide satisfactory, long term performance.

Durability: The test specimen was similar to that shown in Federal Specification TT-S-00230c. [72] The tape was placed on a steel surface glued to a wood block backing (as in the finished panel). Another similar block was placed on top of the tape to form a joint. This simulated joint was compressed and allowed to stand for three days. The joint was further compressed and heated in an oven at 70°C (150°F) for seven days after which time, upon cooling to room temperature, 23°C (73°F), it was subjected to ten cycles of compression and extension. The specimen was recompressed and while under compression reheated in the oven for 16 to 20 hours. After cooling to room temperature and removing the clamps, it was placed in a cold box and stretched while being cooled to -26°C (-15°F). The joint was then blocked open and, after warming to room temperature, examined to see if adhesion had been maintained without permanent deformation. Following the visual examination, the compression extension procedure was repeated nine times in accordance with the Federal Specification mentioned above.

Tenacity: Specimens were prepared by placing the sealant tape on a thin tin sheet and covering the upper surface of the tape with a release paper. The tape specimen was then placed between two wood blocks kept under compression at room temperature for three days, followed by three temperature cycles of 16 hours at 70°C (158°F) and eight hours at – 26°C (– 15°F). After the third cycle, while still at – 26°C, the plate was bent around half of the circumference of a ¼ in diameter mandrel. Absence of cracking after this test was evidence of reliable adhesion.

Water Immersion: Specimens similar to those used for the durability test were held at room temperature under compression for three days and then immersed in water for 14 days. Maintenance of adhesion was an indication of suitable weather resistance.

4.6.2 TEST OF A COMPOSITE PANEL FOR CONDENSATION [73]

The Operation BREAKTHROUGH wall panel described in section 3.3.2 consisted of two skins of fiberglass reinforced polyester laminate separated by a corrugated sheet of the same material. The spaces between the corrugations were filled with mineral wood insulation. The panel was tested with its interior side exposed in a warm humid chamber and the other (exterior) side exposed to the atmosphere in a cold dry chamber in order to observe its behavior with respect to moisture condensation and drying. (See fig. 61.) The top and bottom plates of the wall specimens contained drilled vent holes. In addition, two rows of holes were drilled near the top and bottom of the exterior face to vent the insulated spaces directly to the outside (cold dry chamber) air. Additional holes were drilled in the outside face to facilitate pressure measurements.

The inner surface was left at a constant (nominal room) temperature and humidity. The outside (cold dry chamber) temperature was maintained at -12°C (10°F) for the first week and was then subjected to a 2½ week series of 24 hour cycles. Each cycle included 11½ hours at – 2°C (28°F) and 7 hours at -11°C (12°F), with the remainder of the time being spent in cycling between these two temperatures. Air flow within the wall system was measured both by tracing the movement of refrigerant vapor through the walls and by using compressed air and measuring pressures at different points in the wall cavity.

Moisture accumulation was determined by visual inspection, by weighing, and by water sensors indicating the percentage of moisture in the insulation. No frosting or moisture could be observed during the testing period and the water sensors did not show any water near the outer surface. Weighing indicated only an insignificant gain.

As a result of testing it was concluded that a moisture increase of about 5 percent might be expected over a four to five month period and that air circulation within the panels is greatly restricted as a result of the presence of densely packed insulation, and hence could not be relied on to dry out the interior of the wall panels.

4.6.3 COMPARISON OF MEASURED AND COMPUTER PREDICTED THERMAL PERFORMANCE OF A FOUR BEDROOM WOOD FRAME TOWNHOUSE [74]

The thermal design of a house—heating, cooling, and insulation—has always been very important because of the first cost and operating cost economics involved.

In order to provide an effective design, the architect and mechanical engineer must have reliable techniques for predicting the energy requirements of a building so that a thermally efficient total system can be produced. Computer programs have been developed to handle the tedious mathematical work involved and this test was part of a continuing series to verify the validity of the approach used. The housing unit chosen for test purposes was manufactured by an Operation BREAKTHROUGH HSP in accordance with BREAKTHROUGH Guide Criteria, and the thermal evaluation was made in terms of conditions at two BREAKTHROUGH prototype sites.

Several factory built modules were assembled in a large, controlled atmosphere room to form a complete housing unit representing the end unit of a row house complex. (See fig. 62. Since the housing unit was so large that it nearly filled the laboratory, a picture showing the modules mounted on an outside foundation has been used.) Suitable thermometers, thermocouples, humidity gages, heat flow meters, anemometers, and gas and electric meters were provided for test observations. Since the housing unit would normally be adjacent to another dwelling unit, its presence was simulated by maintaining the temperature on what would have been the common wall at a level that would occur when an adjacent building was present. Energy requirements due to occupancy were also simulated in accordance with an assumed schedule of activities. Outdoor conditions were simulated to represent climatic conditions at two BREAK-THROUGH sites where similar housing was built. One of these was in the north and the other at a southern location. Ten different types of test conditions were used to evaluate the thermal performance of the housing system, including:

1. Northern climate, electric heat, simulated occupancy.
2. Northern climate, gas heat, simulated occupancy.
3. Northern climate, electric heat, no simulated occupancy.
4. Southern climate, gas heat, simulated occupancy.
5. Southern climate, electric heat, no simulated occupancy.

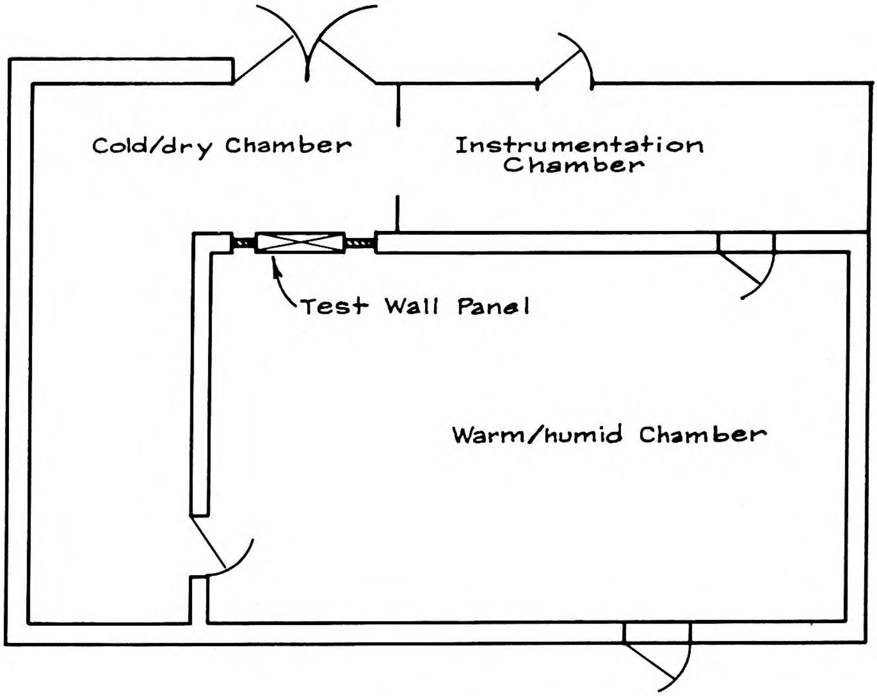

FIGURE 61
SET UP FOR TESTING A SANDWICH PANEL FOR MOISTURE ACCUMULATION

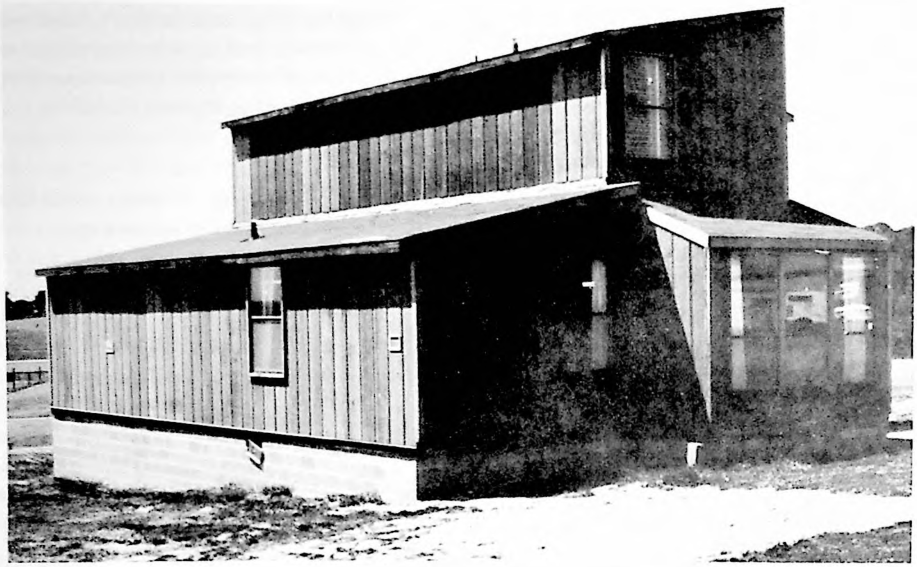

FIGURE 62
HOUSING MODULES USED TO STUDY THERMAL PERFORMANCE

6. Large variation in temperature, electric heat, no simulated occupancy.
7. Steady state (slightly below freezing), electric heat, no simulated occupancy.
8. Pull-down test representing a large drop in outside temperature.
9. Summer cooling test, simulated occupancy.
10. Fall test, heating and cooling on the same day, simulated occupancy.

The tests were carried out by varying the atmospheric (test chamber) conditions to which the building exterior was exposed while maintaining the building interior temperature at 24°C (75°F). Heat flow, temperature variations, and air flow were all measured by appropriate equipment, as were electricity or gas consumption. Results indicated that the variation between predicted and measured energy consumption was small (less than five percent maximum) and hence the validity of the computer program was demonstrated.

Another interesting result was obtained from Tests 3 and 6, which were made with the specific intention of checking the effects of a nighttime temperature setback. An overall daily savings of approximately ten percent was achieved by reducing the temperature 5°C (9°F) for a period of eight hours.

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