26 Apr 1972

Structural Materials and Testings for Low-Cost Housing

Leonard Ru-Liang Wang

STRUCTURAL MATERIALS AND TESTINGS FOR LOW-COST HOUSING

by

Leon Ru-Liang Wang, Sc.D., P.E.*

INTRODUCTION

In the literatures on low-cost housing problems related to urban renewal developments, much work on industrialized housing projects with modular constructions has been reported. There are however, only limited discussions on the development of new materials, research and/or research techniques for low-cost housing.

To fill up this gap, this paper reports and discusses some relatively new materials and testing methods that may be applicable to low-cost housing projects for their economical aspects.

STRUCTURAL MATERIALS

The conventional materials used in construction industries such as metals, reinforced or prestressed concrete, woods, or even clays are well known to us and thus will not be repeated. However, many newly developed composite materials that may have potential use for the low-cost housing projects are worthy to consider. Specifically, this paper reports and discusses three types of composite materials that the writer is familiar or associated with.

Fiber Reinforced Concrete

By definition, fiber reinforced concrete is to mix some kind of fibers into the plastic-like material in order to achieve flexural (tensile) capacity of the material. Without specific details this material would have the following obvious advantages:

1. The labor cost would be reduced because the placing of reinforcements has been eliminated.
2. The thickness of thin slab or shell structures could be further decreased because there will be no need in providing reinforcement protection.
3. New possibility for prefabricated elements.
4. Increasing fatigue life of structures.
5. Realization of water proofs.
6. Greater fire resistance.
7. Time saving in design and construction.

Historically, the idea of randomly mixing fibers of some kind with plastic-like materials is not new. However, systematic and intensive research in the area has not been generated until recently. In 1963, Romualdi and Batson (1, 2) were first to report the investigation of crack arrest mechanism by testing concrete with very closely spaced reinforcements. Working independently, Goldfein (3) investigated the impact and shatter resistance of portland cement mixed with various plastic fibers. He indicated that all fibers investigated increased the impact strength of cement. In 1964 Romualdi and Mandel (4), reported the tensile strength capacity of concrete reinforced with short steel wires. In general, these investigations reported the tensile strength of concrete increased with increasing content and with decreasing spacing of reinforcements.

More informatively, Williamson (5, 6, 7) reported many test results of flexural strength and shock resistance of concrete through the use of various size and lengths of chopped steel wires, glass fibers, and nylon under both static and dynamic tests. It indicated that ultimate flexural strength could be increased 1.5 times (with nylon) to 2.5 times (with steel wire) that of plain concrete.

Later Birkimer and Hosseley (8) in 1968 and Birkimer (9) in 1969, reported further findings on static, dynamic and fracture strength of plain and fibrous concrete. They did not look into the basic mechanism of fiber concrete.

In a very recent report, Shab and Rangan (10) at the Massachusetts Institute of Technology studied the micro-mechanical properties of fiber reinforced concrete. It was observed that significant reinforcing effect was derived after the cracks are initiated in the matrix. The post cracking resistance of fibers was considerably influenced by their lengths, orientation, and fiber stress-strain characteristics.

At Rensselaer Polytechnic Institute, under the direction of the writer, Abbud-Klink (11) has done a thesis investigation on research of randomly oriented fiber glass reinforced concrete named FICRETE. The glass fibers were impregnated with epoxy resin for protecting the glass against alkali action. The mechanical properties and stress-strain relationship of FICRETE were determined for different glass to concrete ratio. Direct tension, compression, bending, bond and creep behavior were investigated. Tests included cylinders, bars, beams, and plates. Experimental data revealed that both tensile, compressive (flexural) strengths increased linearly with the amount of glass fiber contained. Figure 1, shows that with glass content to 0.6% we could achieve tensile strength of fiber reinforced concrete approximately to half of the compressive strength.

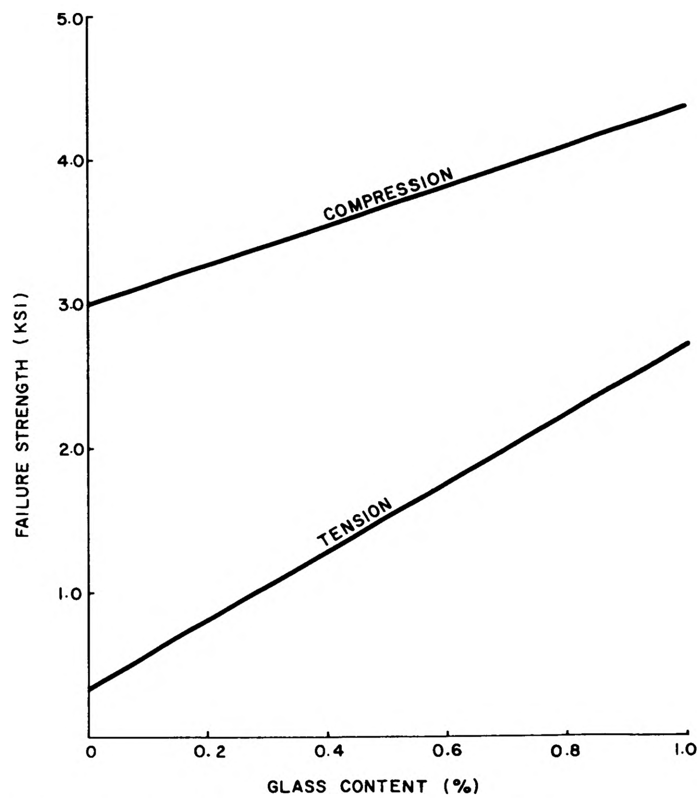

Fig. 1. Failure Strength of Fiber Reinforced Concrete vs. Glass Content

Material with Unconstrained Damped Layers

Earthquake has been a major problem in designing high-rise or low-rise buildings, including low-cost apartment houses. Although no engineer can design a structure which is absolutely safe against an unexpected large earthquake, losses and damages would be reduced if all structures were designed with proper damping capacity so that excessive deformation would be reduced or damped out when large ground motion or dynamic force is applied. For

*Associate Professor of Structures, Rensselaer Polytechnic Institute, Troy, New York 12180.

many many years, the controlling of vibrations response of structures has been a great concern to engineers.

To isolate mechanical vibrations to structures, methods such as machinery balancing (12) and anti-vibrations mounting (13) have been employed. In recent years constrained and unconstrained viscoelastic layers to beams and plates have been studied.

At Rensselaer Polytechnic Institute, a project (14) has been established to investigate experimentally the damping behavior of cantilever beams for different materials coated with different thickness of unconstrained viscoelastic layers.

The vibration was generated either by an initial displacement (free vibration test) or by a vibration exciter (force vibration test). Strains on the beams were measured continuously with time by Sanborn Recorder. The damping characteristics, expressed in terms of logarithmic decrement and the natural frequency, are compared for different materials and for different thickness of viscoelastic coatings.

As expected, the addition of the viscoelastic layers increased the damping behavior of the beams. In one instance, we obtained a critical damping of an aluminum beam with coatings on both sides. It was also observed that the logarithmic decrement for the beams coated on one side is much higher than the beams coated on two sides having the same thickness ratio. Also, the properties and the geometry of the structure had a considerable effect on the amount of damping.

Although it is still a long way to design structure with complete control of damping capacity, it is observed that for building low-cost housing near earthquake zones, structural members coated with some viscoelastic materials may develop very favorable damping capacity to reduce the possibility of damage due to vibrations.

Sandwich Materials

There are many investigations (15, 16) on sandwich constructions. Sandwich material is suitable for low-cost housing projects because the material is relatively inexpensive, rigid, durable, and lightweight. At Rensselaer Polytechnic Institute, Phang (17) has done an investigation on sandwich material with concrete skins and honey cone core. The study showed that this material is structurally and economically feasible.

STRUCTURAL TESTINGS

It is well known that the experimental approach has obvious advantages over the mathematical methods in problems wherein the structural behavior is not understood. However, large scale or prototype experiments are very costly to perform. Small scale model experiments would be extremely advantageous in reducing cost and time to produce sufficient data.

In structural engineering, the problems that are not well understood can be grouped into three distinct types, namely:

A. Eleastic equilibrium or stress distribution problems.
B. Stability or buckling problems.
C. Ultimate strength problems.

Plastic models (18, 19, 20) seem to be very suitable to study equilibrium and buckling problems, because at low stress level, the stress-strain behavior of plastics is practically the same as (linearly elastic) those of prototype materials. Some other advantages of plastic models are summarized as follows:

(1) Plastics have low modula. Thus, structural plastic models can undergo elastically large deformation for favorable measurements. In turn, the loading mechanism is simplified.
(2) Plastic models are recoverable after buckling without changing basic properties of the material. Thus, all structural plastic models can be repeatedly tested to increase reliability of the experiments.
(3) Plastic models can be easily constructed by forming or joining process to arbitrary or complex shapes of shell structures.
(4) The material is readily available.
(5) The cost is low.

However, plastic models cannot be used for ultimate strength study. For ultimate strength problems, one has to use very similar to identical prototype material. At the present time, one will find that microconcrete (21) or mortar may represent concrete characteristics; bronze or brass may be used to simulate steel structures.

Depending on the type of problem studied, a model project in general requires only simple equipment and nominal material cost. The following are a few sample projects:

Stress Analysis of Wind Bracing in a Three Story Frame (22)

The project was to investigate the effectiveness of various types of wind bracing on the control of horizontal deflections of multi-story frames by physical models. A three foot plastic model of a three story frame was constructed and tested. The model was built to be dimensionally similar to a typical frame with 1/10 scale. Both strain gages and dial gages at each level were instrumented.

The types of wind bracings studied are shown in Figure 2. A total of eighteen different types of wind bracings were investigated for horizontal forces and support settlements.

Results were analyzed and compared. Details can be found in the student's report. In conclusion, it was found that it is important and economical to brace the lower level(s) other than the higher level(s) of the frame. It is noted that this type of investigation would be highly cost-effective.

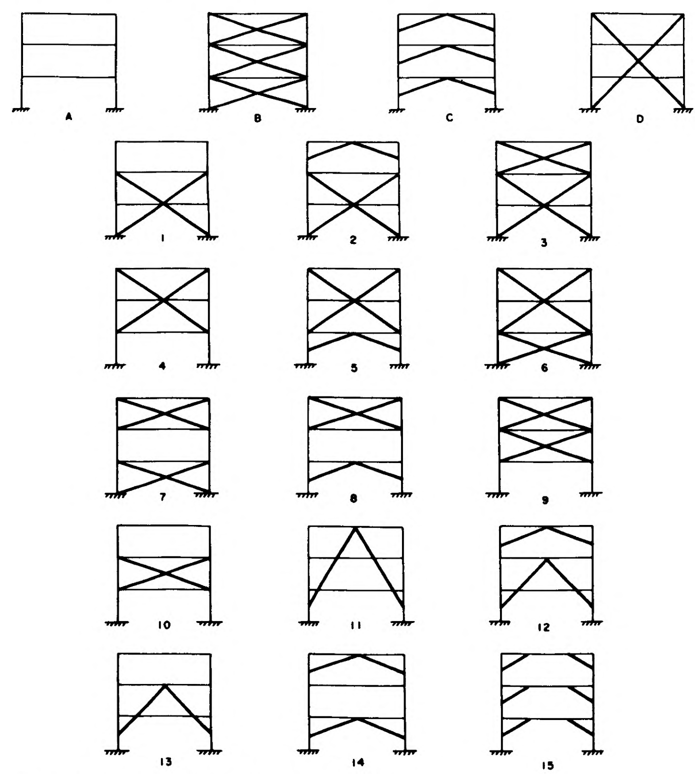

Fig. 2. Study of the Effectiveness of Wind Bracings

Buckling Tests of Shell Structures

In view of the advantages of small scale model analysis, the investigations (20) of edge effect on the buckling of spherical shells has been carried out by plastic models (Figure 3). A total of eight different edge restraint and two external force disturbance conditions were tested. The shells were formed by vacuum forming machines and the pressure was applied with vacuum. The results from this study indicated that the buckling load is sensitive to edge conditions. Again, the project cost was nominal.

Another example (23) was the testing of hyperbolic paraboloids with hanging weights.

Four plastic hyperbolic paraboloids of the warped parallelogram type were joined on edge beams to form a root model, 18 x

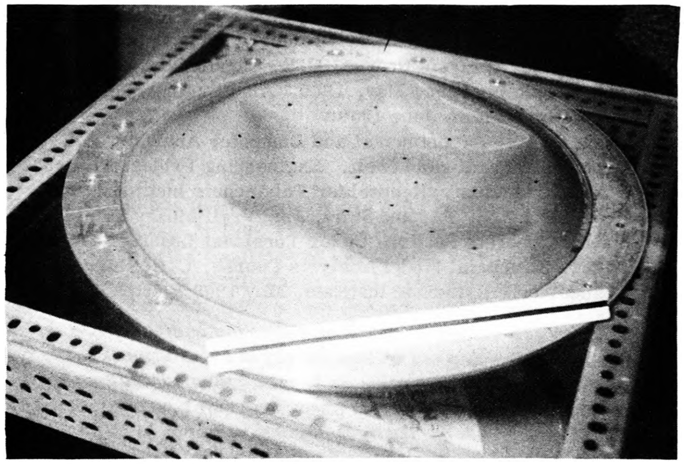

Fig. 3. Buckling Test of Spherical Shell by Vacuum Pressure

24 inches (Figure 4). The shell was supported under rollers, short columns, long columns, and fixed edges and tested separately. Test apparatus and instrumentations were very simple.

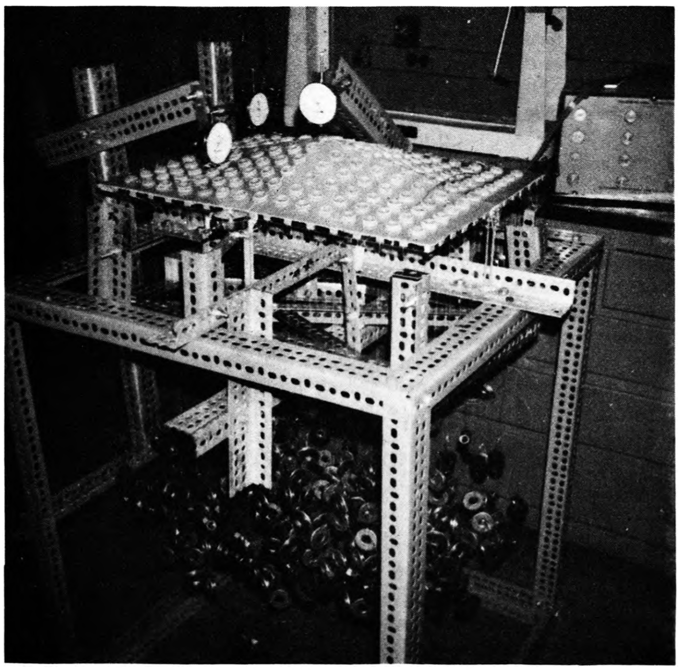

Fig. 4. Test of Hyperbolic Paraboloid Shell by Hanging Weights

Ultimate Strength Tests

Obviously the study of ultimate strength behavior cannot use plastics. It is best to use the original material. One student project (24) was the preliminary study of square concrete section under torsional loading.

The project was to study the contribution of various reinforcements of ultimate torsional strength of a square section 4" x 4" and five feet long. Two plain concrete beams, two beams with longitudinal steel only, two with stirrups only and two fully reinforced beams were tested.

The testing rig consisted of a fixed based collar, a loading collar and a hydraulic loading system including two hydraulic jacks. Displacements were measured by strain gages. Ram loads were measured by aluminum tension load cells. The results show a general trend of increase in torsional strength afforded by the stirrups and longitudinal bars.

CONCLUSIONS

In studying low-cost housing projects, the reduction of cost for analysis and design is important. The structural model testing and the newly developed materials that may be applicable to low-cost housing projects are summarized and briefly discussed. For further information, the readers are encouraged to inspect the original papers.

One may note that the applications of these newly developed materials such as fiber reinforced concrete and small scale structural plastic model testing techniques would not only reduce the cost of the project, but also provide an architectural flexibility to design thin plate or shell structures for low-cost housing.

REFERENCES

1. Romualdi, J.P. and Batson, G.B.: The Behavior of Reinforced Concrete Beams with Closely Spaced Reinforcement. ACI Journal, June 1963, pp. 775-789.
2. Romualdi, J.P. and Batson, G.B.: The Mechanics of Crack Arrest in Concrete. Journal of ASCE EM3, Vol. 89, June 1963, pp. 147-168.
3. Goldfein, S.: Plastic Fibrous Reinforcement for Portland Cement. Tech. Report AD 427-342, U.S. Army Engineer Research and Development Lab., Fort Belvoir, Va., October 1963.
4. Romualdi, J.P. and Mandel, J.A.: Tensile Strength of Concrete Affected by Uniformly Distributed and Closely Spaced Short Length Wire Reinforcements. ACI Journal, June 1964, pp. 657-671.
5. Williamson, G.R.: Fibrous Reinforcement for Portland Cement Concrete. Technical Report No. 2-40, Corps of Engineers, Cincinnati, Ohio, May 1965.
6. Williamson, G.R.: The Use of Fibrous-Reinforced Concrete in Structures Exposed to Explosive Hazards. Miscellaneous Paper No. 5-5, Corps of Engineers, Cincinnati, Ohio, August 1965.
7. Williamson, G.R.: Response of Fibrous Reinforced Concrete to Explosive Loading. Technical Report No. 2-48.
8. Birkimer, D.L. and Hosseley, J.R.: Comparison of Static And Dynamic Behavior of Plain and Fibrous-Reinforced Concrete Cylinders. Technical Report No. 4-69, U.S. Army Engineer Division, Corps of Engineers, Cincinnati, Ohio, December, 1968.
9. Birkimer, D.L.: Critical Normal Fracture Strains of Plain and Steel Wire Fibrous Reinforced Concrete. Technical Report M-1, Construction Engineering Research Laboratories, Champaign, Ill., October 1969.
10. Shab, P.S. and Rangan, R.V.: Some Micromechanical Properties of Fiber Reinforced Concrete. Technical Report R 69-72, Massachusetts Institute of Technology, Dec. 1969.
11. Abbud-Klink, Sami B.: FICRETE - A New Material for Structures. Ph.D. Thesis, Rensselaer Polytechnic Institute, Troy, N.Y. 1967.
12. Anon, J.: A Very Dynamic Balancing Machine. Engineering, London, Vol. 197, 1964.
13. Anon, J.: Anti-Vibration Pads in Building Structure Engineering, London, Vol. 199, 1965.
14. Tasuji, M.E.: An Investigation of Damping Characteristics of Cantilever Beams with Viscoelastic Layers. Engineering Project Report, C.E. Curriculum, Rensselaer Polytechnic Institute, June 1970.
15. United States Department of Agriculture: List of Publications on Sandwich Construction. Forest Service, U.S. Dept. of Agriculture, Dec. 1966.
16. Kuenzi, E.W.: Structural Sandwich Design Criteria. Forest Product Laboratory, United States Department of Agriculture, 1963.
17. Phang, M.K.S.: Structural Behavior of Reinforced Concrete Sandwich Construction. Doctoral Thesis, Rensselaer Polytechnic Institute, June 1970, Troy, N.Y.
18. Little, W.A.: Reliability of Shell Buckling Predictions, Based Upon Experimental Analysis of Plastic Models. Sc.D.

Thesis, C.E. Dept., M.I.T. 1963.
19. Leet, K.J.: The Nature of Buckling in the Hyperbolic Paraboloid, and the Influence of Edge Members on Buckling. Sc.D. Thesis, C.E. Dept., M.I.T., Sept. 1964.
20. Wang, L.R.L.: Buckling of Spherical Shell with Various Boundary Conditions. Sc.D. Thesis, C.E. Dept., M.I.T., June 1965.
21. Alexander, B.F.: Use of Micro-Concrete Models to Predict Flexural Behavior of Reinforced Concrete Structures Under Static Load. Technical Report P63-1. C.E. Dept., Massachusetts Institute of Technology. 1963.
22. Schlein, H., Johnson, M., and Woo, D.: Investigation of Wind Bracing in Multi-Story Frames. Term Paper, Structural Model Analysis Course, C.E. Curriculum, Rensselaer Polytechnic Institute, May, 1969. Also Engineering Project Report by Schlein, June 1969.
23. Stori, J.A.: Experimental and Computer Analysis of A Hyperbolic Paraboloid Shell. Engineering Project Report, C.E. Curriculum. Rensselaer Polytechnic Institute.
24. Pikul, R., Koo, F., and Stori, J.: Preliminary Study of Square Concrete Sections Under Torsional Loading. Term Paper, Structural Model Analysis Course, C.E. Curriculum, Rensselaer Polytechnic Institute, May 1969. Troy, N.Y.