International Symposia on Low Cost Housing Problems

Civil, Architectural and Environmental Engineering Conferences

26 Apr 1972

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Recommended Citation

Tiner, W. D., "Problems Encountered in the Manufacture of Monolithic Concrete Modular Houses" (1972). *International Symposia on Low Cost Housing Problems*. 98.
https://scholarsmine.mst.edu/islchp/98

PROBLEMS ENCOUNTERED IN THE MANUFACTURE OF MONOLITHIC CONCRETE MODULAR HOUSES

by

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INTRODUCTION

Mankind has been attempting to build low cost concrete houses for many years. In 1907 Thomas Alva Edison announced a "new method of building dwellings of small cost." (1) Edison said: "There is nothing particularly novel about my plan: it amounts to the same thing as making a very complicated casting in iron, except that the medium is not so fluid. Someone was bound to do it, and I thought that I might as well be the man, that's all." (1) Edison's announcement stirred up quite a controversy.

Over the next fourteen years more systems were proposed for the building of concrete houses. In 1921 H. A. Mount claimed that Simon Lake, of torpedo boat fame, "has found and removed the flaws in Edison's plan." (2) He, along with Robert C. Lafferty, a New York architect, developed an elaborate modular system that is very similar in many respects to that presently being used by H. B. Zachry Company of San Antonio, Texas. Lake's house module was "12 1/2 x 28 feet." (2) Zachry's module varies in length from 28 to 37 feet and is 13 feet wide.

Lake's plan as stated was ". . . instead of building the house on the lot, necessitating a vast amount of labor for putting up and tearing down expensive forms, he will build monolithic concrete units from standardized forms in well-equipped factories, and deliver the finished house, ready for occupancy, to the lot!" (2) This is exactly what H.B. Zachry Company is proposing and has very nearly succeeded in doing economically.

There is nothing new under the sun, including presumably the problems of building concrete houses, since to date none of these systems have proved very successful. H.B. Zachry's system has an excellent chance for success since the problems inherent in concrete have been recognized and either solved or circumvented.

The remainder of this paper will be devoted to a discussion of these problems and will enumerate several possible solutions to each. Since much of what Zachry has done to solve these problems is proprietary in nature, the solutions will be discussed only in general terms of the approach rather than in specific detail.

PROBLEMS INHERENT IN THE USE OF CONCRETE IN HOUSES

Insulation

One of the most troublesome problems in the use of concrete in houses has been the relatively high thermal conductivity, k, of concrete. This heat transmission capacity causes the interior surfaces of exterior concrete walls to be cold in the late fall, winter, and early spring. When this occurs simultaneously with high humidity condensation takes place.

If the interior temperature of the house is in the range of from 50 degrees F to 90 degrees F, or that range which best supports the growth of molds, then these growths will appear on the walls. This is an untenable situation for the occupant.

The high thermal conductivity of concrete also creates an economic problem for the occupant, since the heat loss in winter and heat gain in summer is high and causes the expense of heating and cooling to be high. In fact, in order to comply with the Federal Housing Authority's (FHA) Minimum Property Standards (MPS), using standard concrete, the thickness of concrete walls required is such as to overcome any economy to be gained by its use and is several times thicker than strength alone would dictate.

One solution to this problem is the reduction of concrete's k factor. Many attempts have been made to accomplish this through the use of such devices as air entrainment, foam, light weight structural aggregates, composite walls (insulation sandwiched in concrete), insulation applied to either the interior or exterior surfaces of the exterior walls, insulating aggregates and various combinations of these.

In order to comply with the FHA MPS as it applies to heat gain and loss, the maximum U factor (BTU gain or loss per hour per square foot of wall per degree Fahrenheit difference between inside and outside air) is 0.2. In order to achieve this with a five inch wall the maximum k factor allowable is approximately 1.2.

Both air entrainment and foam must be applied to such a degree that both the strength and surface hardness are affected if a k=1.2 is to be obtained.

Generally, in order to get a k factor of 1.2, a mix must be designed which will weigh less than 50 pounds per cubic foot (pcf) with a strength of less than 1000 pounds per square inch (psi). The surface of such a wall will be very soft and subject to damage from even the slightest impact and some means must be found to minimize this defect.

If the system involves the use of modules, such as H.B. Zachry's, these strengths will not be sufficient to allow handling and transportation without the use of extreme care and expensive transportation devices.

The use of lightweight structural aggregates such as expanded shale will not, in general, give concrete a low enough k to provide an economical wall by itself. In order to reduce the heat transmission to a satisfactory level, the walls are generally too thick to be economical.

One solution to this thermal conductivity problem has been developed in the composite or sandwich wall.

One approach to the use of the composite wall has been in the development of sandwich panels which are precast in a precast plant and erected on the site. This generally involves the pouring of a concrete surface on one or both sides of a sheet of insulation. The insulation is generally polystyrene or urethane of a closed cell type so that it does not absorb water from the concrete. These panels provide a feasible solution to residential construction, but they present the difficult problems of the field connection of the panels and maintaining undamaged any pre-finish which might be applied in the plant.

Another solution to this problem using the composite wall is the Zachry system, which is a poured monolithic wall and roof system wherein the insulation is inserted in the wall along with the reinforcing steel prior to the pouring of the concrete. Again, a closed cell urethane or styrofoam insulation is used so that water absorption is eliminated.

This sytem, too, has some major drawbacks. In order to minimize materials and weight, the wall thickness is held to five inches. With the insulation, reinforcing steel, electrical conduit and blockouts for windows and doors in the wall, it is necessary to use a very high slump concrete so that it will communicate around these required inserts.

This necessitates a mix which has more water than would be required for the concrete process itself. Therefore, in order to maintain the proper water-cement ratio, cement must be added and this adds cost.

In this system a lightweight expanded shale aggregate is used along with silica sand, an air entraining agent, and a workability agent. The net weight of this wall is 95 pounds per cubic foot.

The results from this wall have been very good insofar as heat transmission is concerned. The economics insofar as materials are concerned is good, but other problems of labor and temperature cracking still need work before the wall can be considered an unqualified success.

The application of insulating panels to the exterior or interior of the concrete walls is also a possible solution to the thermal conductivity problem. This is a good solution since concrete walls, in order to be attractive, must have a texture applied and insulation can be bought today which has a paper cover and can be taped, floated and textured like gypsum board. However, since this insulation is less dense than gypsum, the wall is not as durable as a gypsum board wall. The labor cost of applying the insulation to the surface is probably no greater than installing it in the forms of the composite wall and probably offers some flexibility in wall textures that concrete, by itself, cannot.

A solution to the heat transfer problem which offers considerable promise is the use of an insulating aggregate, providing one can be found that will provide sufficient strength while reducing weight at an economical cost. Various forms of volcanic materials have been used as insulating aggregates for years in roofing systems. These materials can provide good insulation, but generally, not the strength. They also have the problem of high water absorption.

All of these solutions will reduce the thermal conductivity of concrete, but they each affect the solutions of other problems. Obviously a solution that reduces strength beyond certain limits is not satisfactory by itself unless something else is done to provide this strength. No system that neglects to solve the problem of thermal conductivity is going to be acceptable.

Shrinkage

One of the most difficult problems presented by concrete houses is the problem of shrinkage cracks. Since this is one of the most researched problems associated with concrete, anything said here would be superfluous, except that it is a problem and will not be completely eliminated in any modular house that is monolithically cast.

One thing that contributes to shrinkage cracks in the modules is the complicated shape of the module which is further complicated by the necessity of leaving voids in the wall for windows and doors. As already stated, concrete poured in these thin walls must have a high slump which requires excess water and cement. Both of these tend to increase the occurrence of shrinkage cracks.

Since cracks in the walls are not acceptable by an occupant, it is necessary that this problem be solved or circumvented. One solution is to cover the interior of walls with an elastic material which will stretch as the concrete cracks.

One such material is vinyl wall covering. This material, in addition to covering up the problem, also adds accent walls to the house and can give a degree of design flexibility.

Other materials which may work are any of the nylon base paints which will stretch and bridge cracks up to 1/16". These materials have not been tested sufficiently at this time to assure a 100% workable end product. Further testing is underway and the possibility of such a solution looks good.

Weight and Strength

One of the major disadvantages of concrete has been the weight of material required to achieve adequate strength. This is especially true if concrete is used in roof sections where the concrete must support loads in tension, and in systems such as Zachry's where the module must withstand considerable handling. The heavier the module the more difficult the handling and transportation becomes.

Up to a point strength can be maintained while reducing the weight of concrete. However, weight reductions achieved at a constant strength are not sufficient to contribute significantly to either the handling problem or the heat transmission problem.

In order to make an important contribution to the weight problem air entrainment, foam, insulating aggregates, or some esoteric structural shape is required. When significant reductions in weight are achieved by decreasing the density of concrete, the strength is reduced and the durability of the surface of the walls is decreased. In the case of horizontal concrete sections such as the roof, the much lower modulus of elasticity of the low density concretes practically prohibits their use, unless some very good moments of inertia can be achieved by the development of deep cross beams, waffle type slab arrangements, or the addition of reinforcing steel.

In the Zachry system, it is necessary for the modules to be removed from the forms as soon as possible, in 6 to 8 hours after pouring, so that the forms may be re-used. This means that a high early strength must be achieved so that the module can be moved without damage. This strength must be on the order of 1800 psi at 8 hours. Using high early strength cement (Type III) and 1/4" and smaller expanded shale lightweight aggregate with 5% air entrainment, this strength can be obtained in this period during the summer months without steam curing. During the winter months steam curing is necessary for from 3 to 4 hours after about a 3 hour pre-set. Generally, this mix will yield a strength of 3500 psi or more at 7 days and a dry weight of 95 pounds per cubic foot.

Obviously, the heavier the module, the more strength required. Since thermal conductivity, strength, and transportation costs all vary directly with the density or weight, weight reduction is desirable to a point where the strength is just sufficient so that the module can be handled without cracking.

Although Zachry's system has not evolved to the point where the factors of weight, strength, and thermal conductivity are optimized, these factors are being aggressively tested and preliminary evaluations indicate that they can be.

Flexibility of Design

Because of the fact that concrete must be formed and forming costs are considerable, the forms must be designed to get maximum usage in order to be economical. In a panel system, where various panels can be put together to create different types and sizes of structures, the forming systems are neither complicated nor expensive. This type system can be very flexible and as such offers the architect much freedom in design. With this freedom he can create individual houses for the occupant and this will contribute to the marketability of the houses.

In the forming systems required for monolithic modules, this flexibility of design is minimum if it exists at all. This is so because of the impracticability of building a large number of forms in order to achieve flexibility, or because of the expense of manufacture and high labor costs relative to the operation of a universal type form that can produce many different plans.

If a manufacturer decides to produce monolithic modules of concrete he must be content with three or four different floor plans with perhaps four variations of the front elevation of each. These front facades can be varied by changing the front trim of the house.

The more times that a given operation is performed, the less labor it takes to perform it. This means that, in order to achieve the lowest cost, all the houses should be exactly alike. Since this leads to stereotyped subdivisions some variation is desirable. Based on economics, the monolithic house with its lack of flexibility is not too bad after all, since it tends to fulfill the repetitiveness required for economy while allowing just enough variation to prohibit monotony.

The Zachry system is capable of producing two, three, and four bedroom homes with either one or one and one-half baths. These plans can be reversed to achieve either north or south front houses. With this system Zachry could produce 12 different plans with four different facades each. This was accomplished by the use of four sets of forms, each of which could produce a module of either 28 feet or 37 feet in length.

While this does not give Zachry an infinite choice in plans, it does give a sufficiency of variation so that their subdivisions have personality and individuality.

The question then is how much flexibility is desirable in a system for producing low cost houses? Probably only the potential owner in the marketplace has the answer. Based on the experience of the past relative to row houses in the Eastern United States, it would seem that complete flexibility is not a necessity and could, in fact, be bad.

PROBLEMS INHERENT IN THE MODULAR CONCEPT AND ITS MANUFACTURE

Forming

The single most difficult problem encountered in the mass production of modular concrete homes is the development of the forming system for casting this very complicated monolithic shape.

The forming system developed by Zachry in conjunction with the Advanced Construction Equipment Company, a division of Symons Forms, Incorporated, worked fairly well with perhaps a few significant exceptions.

To begin with, the initial premise upon which Zachry based their design called for all of the exterior, and nearly all of the interior, walls to be cast in concrete. This appeared to be a logical criterion since the pouring time required for the house with the interior walls and without the interior walls appeared to be about the same, and the materials cost for the interior walls was, for practical purposes equal, whether they be made from concrete or some form of dry wall. The estimated labor for setting the additional forms and installing the mesh was less than it would be to install the dry wall.

The latter turned out to be in error, and was perhaps due to the design of the forms rather than the original premise. The difficulty arose from the labor required to set the forms. With the two interior walls in each 37 foot long module, there were twelve interior corners to be formed. The original form design called for a hinged corner which could be locked in place. The alignment of the interior wall forms with the base and roof soffit and the setting of these corners was very tedious and time-consuming. Several modifications were made to these corners, but since the wall form was not tied by a hinge or other locating device to the soffit at the bottom of the wall, aligning the corners became a difficult task. The fit between the corners and the walls, even when taped, tended to allow the concrete to pocket. This in turn caused extreme difficulty in the removal of the forms after the concrete had set.

Later in the production run, the interior concrete walls were eliminated in order to minimize this problem. The net effect of this was to reduce the number of interior corners from twelve to four. This produced a module of less cost in the casting area, but increased the cost in the finishing area since these walls had to be replaced by drywall.

This, however, produced some positive advantages, since first, it reduced the overall labor cost without significantly increasing materials costs. Second, by removing these fixed concrete walls an extra degree of freedom of design was attained, since these replacement walls could be located in different places.

Another aspect of the forming system that causes problems is the fact that all materials used in forming concrete are elastic, and under load they are going to deform. No matter how strong the forms are made, some deformation will take place. This is especially so if the forms must be vibrated in order for the concrete to fill all of the voids. Built-in tolerances must be designed into the form or the completed modules will not fit together properly.

In the pouring of the module some external vibration will be required in order to get even extremely high slump concretes to communicate properly. This vibration will be deleterious to the form itself even if it is of steel construction. Strengthening the form is not always the answer to this damage since the stronger the form the more vibration energy must be applied to get the desired effect on the concrete. A balance must be reached in the form design to minimize its deformation under load and allow a moderate amount of vibration without requiring frequent form repair. Even with this balance, assuming it can be achieved, the forms will have to be repaired from time to time.

In designing the forms, consideration should be given to making their operation as automatic as is economically possible. Based on estimates of converting Zachry's forms to fully automatic, the additional cost would probably be about one third the original cost of the forms. This is not excessive, since the steel form's original high cost means that a large number of houses must be produced by their use in order to amortize them. The additional cost of automation then would probably be paid for by labor savings to be achieved by the automation in this large number of houses.

Whether the forms are completely automated or not, serious consideration should be given to making all strippable parts of the form self aligning and self locking, since in a form that is this complicated, the labor required to align the various parts and lock them in place can get to be a sizable percentage of the total labor required in casting.

Redundancy

When modules are stacked, the floor of one box or the ceiling-roof of the one below is not necessary to the function of the building. They are then redundant. Also, when modules are set side by side, one of the two walls of the adjoining boxes is unnecessary to the function of the house and is, therefore, redundant.

While several systems have been developed which have effectively eliminated redundancy in the concrete modular concept, these are in direct opposition to the factory built concept of Simon Lake, since considerable "on-site" finishing must be accomplished in each. In order to have a true modular factory built home one needs a box or a sealable six-sided object. If more than one of these modules is required to make a house, then some redundancy is necessary.

Is this necessarily bad? Depending on the design, the redundant wall's depth can be reduced to one half of a normal wall so it forms a composite wall when put together with the wall of the other module. This in effect reduces the waste material and allows the module to be finished in the factory. This also reduces the weight of the module, which is an advantage.

This cannot always be accomplished due to structural considerations. Where the redundancy is required structurally, such as in a highrise building, the labor saving of modular manufacture will offset the costs of the additional materials required.

This trade off of material for labor could well work to the long run advantage of the modular systems, provided the efficiency of factory labor continues to increase with wages while the efficiency of construction workers remains fixed while wages increase.

Transportation

One problem inherent to all modular systems is transportation. Obviously, the factory manufactured unit must be delivered to the construction site. This fact imposes serious restraints on the designer, for in order to transport anything over the railroads, highways and streets it must comply with height, width, length and weight limitations imposed by the various governing authorities.

The restraint that causes the most difficulties to the designer are the width restrictions. Most states today limit the width of a load over their highways to twelve feet. With the walls taking from five to ten inches, this limits the width of a modular room to something slightly over eleven feet. This is anything but a mammoth room and especially limits living rooms. Some states have modified their width regulations to allow fourteen foot widths and, although this helps, it does not give enough width for spacious rooms. Most railroads have clearance problems if the load width is over eleven feet. If the manufacturer feels he will want to ship by rail then this restraint will govern. If the module is strong enough in the horizontal axis, it can be rotated 90 degrees and shipped on its side. Most railroads could handle a module so rotated provided the height of module and car combined does not exceed 20 feet.

A disadvantage to shipping modules on their side is the additional stresses that the module is subjected to in the rotation process. When the loading is rotated ninety degrees then the stresses are rotated, and the designer must take this into consideration. Most concrete modules such as Zachry's are stronger in the horizontal axis and can be rotated with little or no problem, since they form a deeper box girder when rotated than before. This is not true for such nonconcrete modules as those of U.S. Steel or Sterling Homex.

One serious problem encountered by Zachry was that of placing the module on the lots. At first they used a system that was similar to moving heavy machines such as steam turbines. This was too slow, so Zachry changed his system to a 100 ton motor crane and was able to set twelve modules per day. This seems like a costly method since the rental of such a unit is high. However, in a well planned operation this cost can be held within reasonable limits so that the cost of transporting and placing a house can be held below $250.00 each.

Because of the foregoing, the designer must use all of the ingenuity he has to design a livable house and stay within the dimensional limits imposed by transportation and placing problems.

GOVERNMENT CONTROLS

The designers of industrialized housing systems have complained that the codes and restrictions regulating housing have placed them under undue restraints. While code variations between locales do cause design problems, most of the codes can be complied with economically if one is designing for only one area where the codes are uniform.

It is not the codes that are bad. It is the code variations between locales that are bad. Quite a few state legislatures have recognized this and have developed uniform industrialized housing codes within their states. As would be expected, these codes have been developed by these states independently and they are not uniform between the states that have them. It would seem appropriate for the federal government to establish a national uniform building code for industrialized housing in order to solve this problem. With such a national code, manufacturers would be able to market their houses nationally without costly variations.

To accomplish the complete job of improving the economics of house building, these codes should be written on the basis of performance specifications, rather than on the basis of materials specifications. This would allow the use of new materials as they are developed without the necessity of changing the codes if the materials meet the performance standards. Designers would have more latitude in the use of materials, and manufacturers of products would be encouraged to search for and perfect more economical materials for construction.

CONCLUSIONS

Concrete modular houses have many problems. These problems are all solvable, but none of them is easy to solve. The advantages of durability, long life and economy far outweigh the problems and make the problems worth solving.

Research is now underway in nearly all areas of concrete housing trying to make better, more economical houses for the U.S.A. Perhaps the dreams of Edison and Lake will come true, even though it has taken three quarters of a century to unravel all the negatives that have beset this concept.

REFERENCES

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