Disaster-Resistant Shell Houses

The future started 40 years ago

BY CLOYD E. WARNES

These days, we hear a lot of talk about “concrete houses.” But are these houses really concrete structures? Maybe they’re best described as houses built using concrete walls supporting wood roofs.

Why the distinction? First, although wood-framed roofs do quite well carrying gravity loads, they can fail to sufficiently resist lateral loads and uplift forces from high winds. In contrast, concrete roofs can provide great resistance to gravity, lateral, and uplift forces—with little required in the way of special detailing.

Second, wood is a combustible material, and exposed metal plate connectors of trusses can quickly lose capacity at elevated temperatures. In contrast, a concrete roof is inherently fire resistant.

Relative to wood-framed houses, concrete houses also offer the benefits of superior resistance to insects, rodents, fungi, and water damage; reduced sound transmission; and much higher thermal mass. Clearly, using concrete in the walls but not in the roof (and the floors) fails to capture the many benefits of having a complete concrete envelope.

STRUCTURAL CONSIDERATIONS

If a concrete roof system is used with a concrete wall system and is properly tied to a specially designed floor slab foundation through the wall system, an incredibly strong three-dimensional box or shell is created. I call this type of construction a disaster-resistant shell (DRS). All six sides of the box must be designed for diaphragm action to carry their share of the loads imposed on the building. These types of shell envelopes are illustrated in Fig. 1.

The structural benefits of a DRS include high resistance to:

- **Seismic forces.** In effect, a DRS can be designed to ride seismic “waves,” much like a ship riding the ocean waves, while maintaining its structural integrity;
- **Wind forces.** As shown by the typhoon performance of the houses in Fig. 2, a DRS can resist wind-carried debris and high pressure differentials that can lead to catastrophic failure of a conventional wood-framed system;
- **Flood damage.** Flood waters are unlikely to deform or float a properly designed and constructed all-concrete “box,” and the salvage value of a concrete structural shell system would be far superior to that of a wood-framed house. In cases where damage caused by moving water, mud flows, or snow avalanches is anticipated, special attention should be paid to the design of the foundation elements; and
- **Percussive loads.** An all-concrete DRS can be readily designed to maintain integrity during a blast, impact, or avalanche event.

Concrete roofs can be flat or pitched and can be cast on site using removable concrete forms (RCFs) or specially designed stay-in-place insulating concrete forms (ICFs). For pitches up to 4 in 12, roofs can be cast-in-place if extra care is taken with the concrete consistency and placing and finishing methods. The special methods required for placing concrete at pitches greater than 4 in 12 may make cast-in-place roofs impractical for all but highly skilled concrete contractors. When cast-in-place concrete roofs are left exposed, stamping or texturing and coating the concrete with an appropriate weather-resistant paint can help provide a more traditional appearance. Practice on the island of Guam (annual rainfall around 100 in. [2500 mm]) has been to leave the concrete roof exposed without any additional treatment unless a rare leak occurs and then it is repaired.

Conventional roofing materials tend to be blown off by the high winds, so a coating of some type of liquid waterproofing may be used when there is a concern about future leakage. For roofs with pitches greater than 4 in 12, it’s more practical to place a flat concrete slab like the one shown in Fig. 3 for the primary structure and then build up...
the slope using wood framing as shown in Fig. 4. In this example, the wood roof may be sacrificed in a disaster, but the interior integrity of the home is preserved by the DRS ceiling. This may also be the more practical alternative for constructing intricate roof designs with hips and dormers.

It’s possible that insulated precast elements may be used up to a pitch of about 6 in 12; but as of now, this technology has still not been developed for single-family houses.

**A HISTORY OF SUCCESS**

During the 1960s, two deliberate and almost simultaneous efforts were made to develop disaster-resistant, single-family all-concrete shell houses. Both projects were intended to prove the feasibility of constructing all-concrete, single-family houses and were directed by engineers with strong backgrounds in concrete design and construction. Both had government encouragement and financial support. Independently launched on the island of Guam and in the central valley of California, the efforts were, unfortunately, unheralded in the trade press and mostly ignored in the local press. The developers of these projects were not even aware of the other’s project at the time.

**Guam houses**

In September of 1962 and April of 1963, typhoons Karen and Olive devastated the island of Guam. After each strike, President Kennedy declared Guam a major disaster area and authorized relief aid. Additional aid was subsequently provided via the Guam Rehabilitation Act and the Guam Urban Renewal and Housing Act, both approved on November 4, 1963. The acts led to a decade of capital improvements on the island, including low-cost concrete homes built in subdivisions developed by the Kaiser Company. These homes, designed by structural engineer Alfred A. Yee, are still in use.

Contractors can form and place a low-pitched roof using conventional methods similar to those they use for structural floors or slabs-on-ground. For any roof, it may be necessary to provide intermediate supports for the concrete slab, using either interior walls or beams. As the sequence in Fig. 5 shows, edge support and ridge beams are also generally required with pitched roofs. Structural engineers may also wish to investigate the possible economies that might be afforded by an alternative folded plate design. Figure 5(d) illustrates the alignment of the ICF planks for a cast-in-place roof deck. The same alignment as the ICF plank forms shown in the illustration could be used if precast hollow-core planks were selected as an alternative to a cast-in-place roof.

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Houses like the one shown in Fig. 6 were constructed with tilt-up concrete walls and cast-in-place roof slabs. The floor slabs were constructed as grids because they also served as floating mat foundations and the grid beams added stiffness to the mats. All six planes of the box were securely
connected to each other to assure they would act together to resist external forces.

In an e-mail message to me in October of 2006, Yee wrote, “The Dededo houses have been in existence for 40-plus years, and they have gone through many heavy typhoons that make Katrina look like only a rainstorm. There were typhoons where winds were recorded at 234 mph [377 km/h] when the anemometer broke. Whatever they were, no one knows!”

Yee also commented on a couple of earthquakes that occurred in the area, stating “We have gone through earthquakes of Richter Scale 8.1. Some tall buildings were damaged beyond repair in this occurrence and had to be demolished, but the Dededo houses did not even suffer any cracking.” He continued: “Last year, we also had a Richter Scale 6.3 seismic occurrence. Of the thousands of houses we built with precast, not a single bit of damage was ever recorded from typhoons or seismic action. They were built like matchboxes with many interior walls going in two directions. You can almost imagine a giant picking these boxes up and dropping them on the ground with no damage.”

Contemporary houses in Guam, such as the one shown in Fig. 7, are constructed using the same all-concrete shell principles as the Dededo houses were over 40 years ago. The new houses, however, reflect more traditional styling and can be difficult to distinguish from houses built in the continental U.S.

**California houses**

Also during the mid 1960s, the California Department of Housing and Community Development initiated a demonstration project to solicit industry solutions to constructing low-cost houses for migrant agricultural workers. With funds from a federal grant, a special program was established to construct...
demonstration housing units at three housing authorities: Wasco, Gridley, and Linnell.

The state invited proposals from the associations representing conventional wood framing, cement and concrete, and building systems industries. The Portland Cement Association (PCA) office in California assigned Charles L. Fries, then Regional Housing Engineer, and me, State and Federal Agencies demonstration housing units at three
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As the demonstration program developed, it became apparent that the cement and concrete industries had very little to offer in the way of a nonproprietary solution that could be built anywhere in the state by general building contractors. Accordingly, PCA assigned resources to develop a generic concrete single-family house design. One of the most important criteria was that the design had to be suitable for construction by those already involved in building houses—carpenters and small contractors. While the house was purposely kept small, it was designed to incorporate the features that would be desirable in a house of any size as it captured the inherent benefits of concrete as a building material.

We decided to design the prototype as a concrete box-frame, with all six sides of the box serving as diaphragms. This required that the floor slab, roof, and walls be constructed of reinforced concrete. As with the Guam houses, the walls were created with tilt-up panels. With the goal of keeping the panels light so they could be erected with the small derrick cranes common on automobile wrecker trucks from that period, we designed the tilt-up wall panels to be only 4 ft (1.2 m) wide. An example of these houses is shown in Fig. 8.
ACI member Cloyd “Joe” E. Warnes is Managing Partner of CPM Associates, a consulting firm that specializes in design and construction of concrete houses. He is a member of ACI Committees 439, Steel Reinforcement, 560, Design and Construction with Insulating Concrete Forms; and Joint ACI-ASCE Committee, 550, Precast Concrete Structures. Following 17 years with the Portland Cement Association, he entered the concrete construction field. He has been involved in the management of several international projects, mostly in the Middle East. For 10 years, he conducted seminars on project management and precast concrete construction in various countries in the Middle East and North Africa. For several years after the break up of the Soviet Union, he mentored indigenous contractors on behalf of the USAID program in Romania, Russia, and Poland. He is designing and constructing ICF shell houses in a relatively severe earthquake region of Romania.

CONCRETE WALL SYSTEMS FOR TODAY

There are a number of concrete wall types capable of supporting a concrete roof system. Traditional cast-in-place concrete walls formed with RCFs, tilt-up concrete panels, and concrete masonry have been with us for a long time. Trade associations have been marketing precast concrete walls (both plant- and site-cast) for several decades. More recently, cast-in-place concrete walls are being constructed using ICFs. Until recently, precast and traditional cast-in-place concrete walls for construction of single-family homes haven’t been particularly successful in gaining market share. Even successful demonstration projects and extraordinary spikes in lumber costs haven’t driven builders to these concrete alternatives. Cast-in-place concrete walls constructed using ICFs, however, have made significant gains. Why?

I believe the origins of this growing success are based in the U.S. tradition of building wood-framed housing using prescriptive design rules. This tradition has, in effect, created a house construction industry dominated by carpenters. Because ICF units are readily assembled using common carpentry techniques, and because the necessary finish materials are much the same as those used in traditional wood-framed construction, ICFs have been adopted as one of the construction systems within the carpenters’ purview.

BECOMING A REALITY

For a concrete house to function as a DRS, it must have reinforced concrete walls as well as a reinforced concrete ceiling or roof and floor. It can then be analyzed as a box assembly, with each side designed to resist both out-of-plane and in-plane loading. To act as diaphragms, each of the six sides of the box must be adequately connected at its interfaces with other sides, using boundary element technology.

Houses constructed with DRS technology have performed very well under extreme seismic and wind loads. The introduction of ICFs makes the universal achievement of all-concrete single-family houses a practical reality for the first time in North American house construction history. This technology also makes it possible for carpenters, who currently control most single-family residential construction sites, to play a dominant role in the development of all-concrete house construction as a generic residential building system across North America.

Selected for reader interest by the editors.