Homes that work: practical, energy-efficient residential designs

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Abstract

This paper discusses four approaches to achieve excellent energy performance and comfort in recently–built homes in the western US. A home in Northern California is a passive solar structure built in the shape of a red- tailed hawk. Its principal structural and insulating material is Rastra™, made from 85% recycled Styrofoam and cement. A home near Colorado Springs, Colorado is the winner of a "best in category" Energy Star award. It has a number of clever features that keep energy demand low. In spite of quite hot summer days in Colorado Springs, the home is passively cooled, daylit, and quite comfortable. A home in Tucson, Arizona represents a class of new homes which have quite low cooling bills in spite of a severe desert climate. The secret is heavy insulation and careful air sealing techniques combined with enclosing the HVAC system within the conditioned envelope. Finally, the Snug House is very inexpensive to build, yet performs quite well in summer and winter in a variety of climates because it is coupled to the earth using an insulation system that provides the structure with the virtues of a cave without the depravities of being underground. All of these homes would perform well in all but the coldest of European climates.

Introduction

Good energy performance in new homes depends on a number of factors, the most important of which are excellent insulation and careful air sealing. Indoor air quality is ensured by minimizing sources of pollutants within the conditioned envelope and employing controlled ventilating strategies that supply adequate fresh air without compromising energy efficiency or causing pressure imbalances. The climate in the southwest of the United States is quite arid and sunny. The lack of clouds creates radiational cooling which lowers temperatures at night in all seasons. Hence, day/night temperature differences are typically 17 to 22 degrees C (30 to 40 F) in the summer and 28 to 33 C (50 to 60 F) in the winter. Accordingly, successful building designs include substantial thermal mass inside the conditioned envelope to dampen the effects of changing temperatures and direct beam solar radiation. In addition, careful attention to glazing characteristics and shading devices is necessary to take advantage of solar gain during the heating season while limiting solar heating effects during the cooling season.

Rastra Homes

"Sunhawk" is the name of a 270 m^2 (2 900 ft^2), passively-solar-heated home recently built near Hopland, California on a mountain about 40 km east of the Pacific Ocean, 160 km north of San Francisco. Summertime temperatures are frequently 43 C (110 F) in the afternoon; wintertime temperatures fall well below freezing. A grid-free home with both micro-hydro and photovoltaic systems for electricity, Sunhawk also includes daylighting and a novel cooling system that relies on deep earth tubes. During the cooling season, ventilation air is drawn from a pair of 46 m (150 ft) long, 30 cm (12 in) diameter tubes from an adjacent wooded area

Figure 1. *Sunhawk south elevation.*

Figure 2. *Rastra sample.*

to the inside of the structure. The tubes are buried 2.7 m (9 ft) deep, down where the soil is at about 20 C (68 F) for most of the year.

As shown in Figure 1, the design was inspired by a red-tailed hawk, where the tail feathers point from southeast to southwest. There is a shading device between the lower tier of fixed glazing and the upper tier. The lower tier of glazing is used for solar heat gain during the winter, so has a relatively high solar heat gain coefficient. The upper glazing functions primarily to supply daylighting, so has a high visual transmittance. The fixed horizontal element between glazings functions as a shade for the lower glazing during shoulder months and the summer. Since its top surface is diffusely reflective, it also enhances the transmission of daylight through the upper glazing onto the ceiling of the great room at the south of the home.

Rastra™, a building material composed of 85 percent recycled styrofoam and 15 percent Portland cement, is used extensively in the building. It serves as structural wall, supplies both thermal mass and insulation, and functions as a base for stucco, plaster, or other finishing materials (Fig. 2). The material is delivered in 3 m (10 ft) long blocks that are 38 cm (15 in) high. The blocks are available in 25, 30, and 36 cm (10, 12, 14 in) thicknesses; Sunhawk is constructed of 30 cm (12 in) blocks. These may be handled easily by two workers, who seal the joints with urethane foam and carve out spaces for wiring and plumbing using routers and electric chain saws. The blocks contain hollow cores that run through their centers horizontally and vertically which are filled with reinforced concrete after the walls are laid up. The resulting web provides strength for the walls as well as thermal mass. This building technique has been approved by California's building codes, whose structural requirements are quite stringent owing to the high frequency of earthquakes in the area. Over 5 million Rastra panels have been sold world wide, most in Saudi Arabia and Austria, and there are over 2 000 Rastra homes in the US (Holik 2003). First costs of homes built with Rastra are about equal to conventional building costs, but lifetime costs are substantially lower owing to excellent energy performance and low maintenance.

The insulating value of walls made of Rastra (with a rebar-laced concrete web) has been measured by several laboratories in Europe and the US. Steady state thermal resistance (R-values) are 1.93 ($11_{\text{I-P}}$) for the 25 cm (10 in) thick wall, 2.87 ($16.3_{\text{I-P}}$) for the 30 cm (12 in) wall and 4.0 m^{2}K/W ($22.7_{\text{I-P}}$) for the 36 cm (14 in) wall. However, since mass is within the insulated space in the case of Rastra, it is useful to ask what would be the equivalent insulating value of a conventional wood frame dwelling to achieve identical heating and sensible cooling loads as a home whose walls are constructed of Rastra. A team at the Building Technology Center of the Oak Ridge National Laboratory (ORNL) undertook an analysis of this question using an hourly simulation model (DOE 2.1E) informed by extensive full-scale laboratory testing (Kosny et al, 1999). The answer is a complex function of climate zone and the dynamic response of homes to changing conditions. The researchers expressed the result as a "Dynamic Benefit for Massive Systems" (DBSM) factor which is used as a multiplier of the steady state R value. In order to achieve the same thermal performance as a Rastra dwelling, the R-value of the walls of a wood frame building would have to be approximately double that of Rastra walls in most climate areas; DBSM values range from 1.79 in Miami, FL through 2.05 in Minneapolis, MN, to 2.17 in Phoenix, AZ.

Of course, the energy performance of actual dwellings is of central importance. Sunhawk, which cost approximately 2 000 Euro per m^2 (\$200 per ft^2), is self-sustained so has no energy bill. Fig. 3 shows a 270 m^2 (2 900 ft^2), three story Rastra dwelling in the Phoenix area that is partially buried in the side of a south-facing slope. In the mild heating season, a heat pump is occasionally used in the morning to supply warmth that passive solar takes care of for the rest of the day. Overhangs prevent direct beam solar during the shoulder seasons and summer. Cooling is primarily supplied by a 1 133 l/s (2 400 cfm) evaporative cooler, supplemented when necessary by a pair of 8 800 W (2.5 ton) chillers. The home has a baseload consumption of 550 kWh/month (1 980 MJ/month). In 2001, heating energy totalled 2 000 kWh (7 200 MJ) for the season and cooling in this desert climate totalled 5 250 kWh (18 900 MJ).

The home uses clear, double-glazed windows with aluminium frames. Energy performance would be enhanced by using specularly-selective glazing with insulated framing members.

Tierra Concrete Homes

A Colorado-based custom home builder specializes in energy-efficient solar heated structures fabricated of concrete walls with exterior insulating panels (Tierra Concrete Homes, 2003). After the building site is prepared, forms for pouring both interior and exterior walls are fabricated on site and laid out on flat ground. Rigid insulation and rebar are laid in place and panels are poured. The walls include provisions for doors, windows, wiring, fixtures for mating panels to one another, and supports for subsequent stucco finish. When the concrete is cured, a crane and work crew put up

Figure 3. *Phoenix Rastra home, south elevation.*

the entire dwelling in one to two working days. Careful attention is paid to ensuring that insulation is continuous and the structures are very carefully air sealed. Specularly-selective glazing, most of which is on the south-facing facade, is employed, as are shading devices to limit summertime solar gain. The result is a tight, well-insulated structure, most of whose mass is within the conditioned envelope.

The 362 m^2 (3 900 ft^2) home shown in Fig. 4 is just north of Colorado Springs, Colorado, where winters are cold and summers are very hot and dry. As a consequence, virtually all conventional homes in the area require air conditioning, whereas this one does not. It relies on nocturnal natural cooling via stack-effect pressure difference between operable dampers and windows at the bottom and top of the envelope supplemented by fresh air from a heat recovery ventilator (HRV). The HRV is also employed during the heating season to supply fresh air to this very tight structure. Most heating is supplied by passive solar; the sun's rays strike massive, dark-stained concrete floors on the three stories in the home. The bottom two floors are laced with a network of polypropylene pipes which circulate water to ensure even heating of the slab throughout the home. When needed, hot water from an active solar heater is used to heat the slab, which is backed up by a small gas-fired boiler.

The home's fenestration is designed to supply natural lighting in most spaces and both interior and exterior electric lighting employ compact fluorescent fixtures. Wall insulation has an R value of 3.9 ($22_{\text{I-P}}$) and it goes into the earth 0.5 m (20 in). R-1.8 ($10_{\text{I-P}}$) rigid insulation is under the basement floor, and the ceiling is insulated to R-6.7 ($38_{\text{I-P}}$). The home cost 1 200 Euro per m^2 ($120 per ft^2). All Tierra Concrete Homes are designed to exceed Energy Star™ standards (EPA, 2003), and the builder has won a number of awards for excellence in energy performance. Importantly, with all house systems off during seasonal temperature extremes from-23 C (-10 F) to 38 C (100 F), the indoor temperature of Tierra homes does not drop below 13 C (55 F) in the winter, nor does it exceed 27 C (80 F) in the summer (Judkoff et al, 1997). This is due to the combination of earth coupling, insulation, air sealing, thermal mass, fenestration, and passive solar.

Pulte Homes

Pulte is one of largest production home builders in the US (280 000 homes built) and heavily markets the energy efficient features of its homes (Pulte, 2003). In Tucson, Arizona, a desert climate, Pulte's homes are slab-on-grade structures with 5 cm x 15 cm on 60 cm centers (2 in x 4 in on 24 in centers) wood frame walls (R-3.5) (R-$20_{\text{I-P}}$) with wood truss attics (Fig. 5). The conditioned envelope of these homes extends into the attic, which houses the air handler, supply and return ducts, and "jump" ducts that serve to keep all spaces within the envelope at constant pressures regardless of the configuration of interior doors. The ducts are carefully air sealed and insulated. Cellulose insulation is blown into a net in the attic immediately below the roof level to R-5.3 ($30_{\text{I-P}}$). As a consequence, temperatures in the attic do not vary substantially from those in the space below, and both the air handler and ducts are within the conditioned space.

Figure 4. *Tierra Concrete Home near Colorado Springs, CO, south elevation.*

Figure 5. *Pulte 132 m^2 "Harmony" home in Tucson, AZ; guaranteed space heating < 38 Euro/month.*

High quality, specularly-selective glazing is used in windows, and well-insulated doors are also employed. Pulte homes are carefully air sealed and construction details assiduously avoid thermal bridging. Most employ air-coupled heat pumps with a seasonal coefficient of performance of 3.5 (SEER 12) and all include continual, low-level ventilation that employs the HVAC system's ducts. When gas-burning appliances are employed within the conditioned envelope, they are closed-combustion devices. As a result, Pulte homes are comfortable in all seasons and energy use for space conditioning is guaranteed not to exceed a modest monthly cost, specified in the purchase contract. Typical numbers in Tucson are ~40 Euro ($40) per month for a 130 m^2 (1 400 ft^2) home. A recent evaluation shows that ~5% of the homes exceed the guaranteed cost – and the utility reimburses homeowners for the difference between actual costs and the guaranteed cost. In the few cases when the differences are substantial, homes are inspected and repaired as needed. More important, approx. half of the homes participating in the program have utility bills that average half of the guaranteed rate (Kinney 2003).

In general, window configurations are not chosen to take advantage of orientation to the sun, but rather are a function of the locus of next-door neighbours and view. In predominantly cooling climates, there is only a small energy penalty

Figure 6. *First Snug Home built in Upstate New York by Paul Howells, inventor of the concept.*

for non-optimal window location, but in predominantly heating climates with good solar availability, the heating energy penalty can be as much as 40%. No facade has heavy fenestration, overall window area being less than 15% of wall area in most models. Pulte homes are sold for about 1 100 Euro per m^2 (\$110 per ft^2) and are built to exceed both Energy Star™ and Building America™ standards (Building America, 2003).

Snug Homes

The "Snug Home" is a construction technique aimed at producing very energy efficient homes whose labor and materials costs are substantially below those of most homes, roughly 500 Euro per m^2 (\$50 per ft^2). Instead of a poured concrete foundation, they are supported by pressure-treated wood poles placed on 2.4 m (8 ft) centers in 1.5 m (5 ft) deep holes that have a concrete plug in the bottom. Trenches 1.2 m (4 ft) deep are dug between the poles to accommodate 10 to 15 cm (4 to 6 in) thick closed-cell insulation. The perimeter insulation is used to define the edges of a concrete slab. Five by 10 cm (2 in x 4 in) framing members are installed horizontally on 0.6 m (2 ft) centers inside and outside the poles to form a 32 cm (12.5 in) thick wall. A sturdy plastic vapor barrier is installed next to the inside surfaces of the poles. It is mated with the below-slab and ceiling vapor barriers via overlapping and silicon-based caulk to achieve a continuous seal. Oriented strand board is glued and nailed to the outside of the structure, then the siding of choice is affixed, for example, shingles or stucco. Cellulose insulation is blown into the space between the vapor barrier and oriented strand board as well as into the attic. Plumbing, wiring, and ducts for the HRV are installed in the wall spaces on the inside of the vapor barrier. Then this space is insulated with R-1.9 ($11_{I\text{-}P}$) batt insulation and dry wall or other interior finishing material is installed. High-quality windows are used to ensure solar gain in the winter and both overhangs and exterior shading are employed to limit summertime heating.

The result is a very tight, well-insulated structure [R-3.9 ($22_{I\text{-}P}$) perimeter insulation, R-7.4 ($42_{I\text{-}P}$) wall insulation, R-8.8 ($50_{I\text{-}P}$) ceiling insulation] that is coupled to the earth (Fig. 6). Deep earth temperatures approximate the annual mean of air temperatures--in the southwestern US, these range from 9 to 20 C (48 to 67 F). Earth-coupled structures such as the Snug House resist going below deep earth temperature even during extended cold spells in the winter – and their summertime performance is substantially enhanced as well. Thus the earth itself functions as thermal mass, and perimeter insulation ensures that the portion of the earth close to the surface whose temperature varies with season is substantially outside of the thermal envelope.

Toward experimenting with the technique in a dry, mountainous climate in the southwestern US, the author built a test structure at 2 380 m (7 800 ft) above sea level near Boulder, CO, where deep earth temperature is approximately 9 C (48 F). Built according to Snug House principles with only 0.9 m^2 (9 ft^2)of fenestration (it's south facing), the structure was not heated at all (save a brief period of the 2002-2003 winter to collect performance data). During the coldest period of the year, when outside temperatures were at –15 C (5 F), the inside temperature never descended below 3 C (36 F). In mid-December, 2002, the structure was heated to 20 C (68 F) by a 900 W space heater while tracking inside-outside air temperature. After reaching steady state conditions, the structure consumed only 0.02 MJ/m^2/C (1 Btu/sq ft/heating degree day). This is about 15% of the consumption of conventional new homes in the southwestern US and coheres with results achieved by Snug Homes in more severe climate areas of New York State.

Conclusions

A number of techniques for achieving tight, well-insulated homes with interior mass are being developed in the US and many builders have mastered techniques for minimizing convective and conductive losses without sacrificing indoor air quality or design aesthetics. In general, the best performance is achieved by homes that respect solar orientation and use up-to-date fenestration and shading tactics to take advantage of solar heating only when it is needed while limiting solar heat gain when it is not. Using the earth to supply thermal mass is a promising tactic that can be usefully employed in lower-cost housing whose energy performance and comfort are exemplary. Appropriately controlled heat recovery ventilation systems can enhance energy performance while ensuring good indoor air quality.

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