PDHonline Course C651 (4 PDH)

Tornado Resistant Homes

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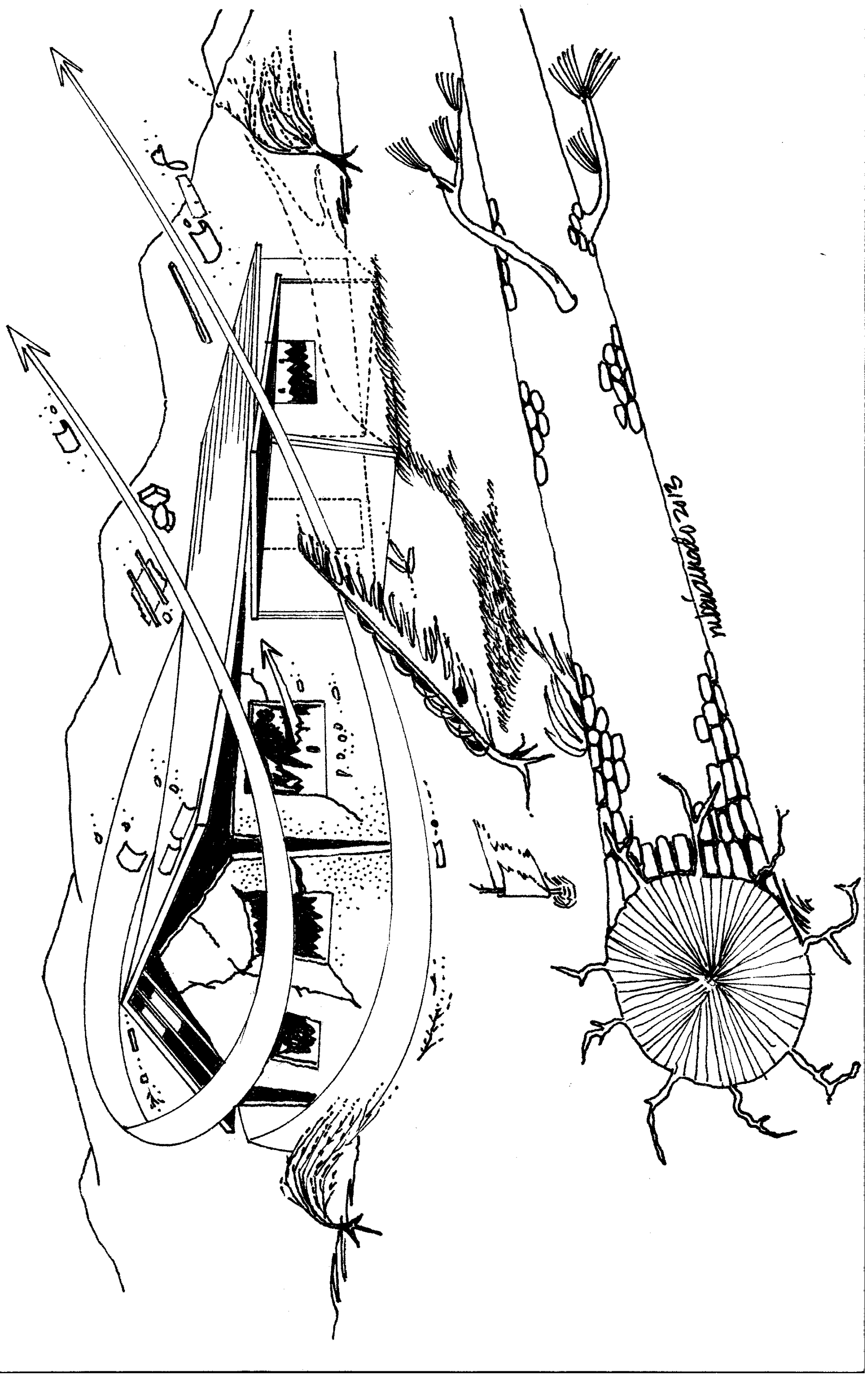
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Tornado Resistant Homes

Ruben A. Gomez, P.E.

1.0 PROLOGUE

Quite often we read or hear from the news media of how tornadoes destroy homes and entire neighborhoods with the resulting loss of lives, limbs and personal property. Those are indeed very sad news; however, it is even sadder to know that it does not need to be that way. Houses can be designed and built to stand to the high winds of the strongest hurricanes and tornadoes.

On the other hand, we have also heard from our colleague engineers referring to tornado resistant structures as an impossibility and therefore something we need to accept as an inevitable reality. Those so poorly trained have publicly advocated on the unfounded fact that tornado resistant homes are either unattainable or that their construction is expensive beyond practicality. Both contentions are wrong, tornado resistant homes are not only possible to achieve but the added construction cost is justifiable and within reason. In this course we will see how houses can be designed and built to resist such calamities and how we engineers have failed to demonstrate how such damage can be brought under control with the resulting preservation of human life and personal property in such a way that we fulfilled our obligation to protect the health, life and welfare of our fellow citizens as it is predicated by the creating laws of the professional engineering licensing boards in most states.

In the same manner, relentless lobbies from powerful business interests have propelled the concept that the pursuit of tornado safe homes is not only nearly impossible, but that it is so helplessly expensive that it would become an absurdity or an exercise in futility. Further, the author’s voice has been often smothered by rebuttals claiming that building strong homes would be bad for the economy, and further, that we should continue building houses of wood sticks, pressed board and paper so when the high winds come they get wiped out and have to be rebuild as an incentive to the cash flow of the industry, never mind how many lives and how much personal property gets lost in the process. To advocate for such insanity is inconceivable, yet it has been the prevailing justifying criteria going on for decades.

Large multistoried buildings endeavored by their enormous weight, size and configurations are in more cases than not inherently tornado resistant, except for their fenestration and facade panels, therefore they will not be covered in this course.

When it comes to schools, the way they were built in the twentieth-century and as they are still being built in this century, are extremely vulnerable to tornadoes and other Acts of Nature (not to make God to appear as the villain). In spite of the fact that the civil authorities see them as the handy and natural choice for public shelters, they do not have the inherent strength for such purpose. Since that being the case, common sense dictates that they should be built with provisions for designated and adequate tornado shelters able to stand up to the fury of Nature.

2.0 THE LOGICAL ALTERNATIVE

As the logical alternative to the method of "wood sticks" mentioned above, with thousand of joints prone to failure, and only taking a few of them to fail to unleash a progressive collapse of the entire structure, it is proposed herein a proven solution: the concrete home, which when properly designed and built there will be no fear of wind failure, and further, it is not susceptible to termite attack, it is incombustible, little or no maintenance to worry about, extremely long lasting and a life expectancy exceeding one hundred years.

First we must begin by mentioning the concrete dome as an extremely strong structure which can be designed, and with very little added cost built to withstand the highest winds that nature can dish out. We recommend the reading of our course titled "Dome Design: Neither Intricate Nor Difficult" which covers a large portion of what there is to know on the design and construction of such structures.

Although domes are a natural alternative to dealing with the problem at hand, some architectural "scholars" object and even reject the idea of the spherical dome for their form and their generation of non-rectangular rooms and living spaces. Having taken that objection as a reality check from the detractors, we have moved to show how the basic principles of design can be applied to a conventional rectangular house and with small additional cost, convert it into a tornado resistant construction which qualities are far superior to those of the traditional "competitive" house design.

In this course we will bring to the readers a fairly detailed example of what can be done, within reason, to achieve the requirements of tornado resistant design. Since we will use reinforced concrete masonry for the walls, here is a reproduction of the conclusions reached by the Federal Emergency Management Administration (FEMA) in its 1993 report issued after evaluation of the wind damages caused by the August 24, 1992 Hurricane Andrew. FEMA indicated that after examining hundreds of cases, failure in masonry walls were attributable to one or more of the following deficiencies:

a. lack or inadequacy of wall vertical reinforcement

b. inadequate splicing of reinforcing bars

c. poor mortar joints between walls, and concrete slabs

d. lack of or inadequate tie-beams, horizontal reinforcement or tie-columns

e. lack or inadequate ties or straps between walls and the roof structure.

Such deficiencies have no place in well designed masonry construction; however, we will devote particular emphasis to address those comments in the accompanying details.

3.0 CHARACTERISTICS OF A TORNADO

Following the strategically based old principle of "know your enemy", here is what the design engineer needs to know about tornadoes and their destructive force, to be able to respond with a design adjusted to the conditions of their reality:

A tornado is a powerful counter-clockwise (in the northern hemisphere) rotating air column generally adopting the form of a spiraling condensation funnel with its wide end in contact with a cumulus-nimbus cloud formation and its narrow end touching the surface of the earth, that end is normally surrounded by a ring of dust and debris rotating on the outside. Similarly to hurricanes, tornadoes have a clear, calmed center with extremely low barometric pressure. Characteristically, temperature tends to decrease and moisture content to increase in the immediate vicinity of a tornado.

Most available scales to rate the strength of tornadoes are based on the damage caused on their path. The *Fujita Scale* (F0 through F5) and its updated *Enhanced Fujita Scale* (EF0 through EF5) are well known amongst meteorologists. While the F0 is the weakest category where trees get uprooted and phone booths blown away, but damage to buildings is minimal. On the other hand, category F5 corresponds to damage described as common buildings being overturned and conventional houses flattened to the ground. Another well known and accepted scale has been created by the Tornado & Storm Research Organization (TORRO) with categories varying from T0 for weak tornadoes to T11 for the most powerful twisters.

In the United States there is an average of 1,200 tornadoes every year and 80% of them are within categories F0 and F1 (T0 through T3) with wind speeds less than 120 MPH, while about 1% are designated as violent and are in the categories F4 and F5 (T8 through T11) with wind speeds of 300 MPH. Most of the latter taking place within the so called *Tornado Alley* in the central plains of the United States.

A further classification of the *Fujita Scale* has designated three main groups of twisters: F0-F1 as a "weak" class with winds below 120 MPH; F2-F3 as "strong" class with winds in the 200 MPH speed; and the rarest of them all, the F4-F5 "violent" class with winds in the 300 MPH speed level.

Although there are some similarities between hurricanes and tornadoes, there are also significant differences. While hurricanes are powerful enough to develop sustained wind speeds of up to 160 MPH and because of their large diameter may siege a given structure for hours on end, they also have a high degree of predictability. Tornadoes on the other hand, are very unpredictable, have a small diameter and although may develop winds of 300 MPH and higher, their highly dynamic pounding may only last for a few short minutes.

4.0 BASIS OF DESIGN

As in any endeavor of basic survivalism, pure engineering design should be based on the mere probability of occurrence. Therefore, if we dismiss the top 1% of violent tornado occurrence as a remote probability, we must then embrace the next step down as the reasonable basis for design. With such consideration in mind, we have chosen 250 MPH as the design wind speed pattern for all buildings outside and 300-320 MPH for those within the Tornado Alley region of the United States.

For the calculation of the velocity pressure (q_z) in pounds per square foot, we will use the formula recommended by the American Society of Civil Engineers ASCE 7-98, Standard 6.0:

$$\mathbf{q_z = 0.00256\ K_z\ K_{zt}\ K_d\ V^2\ I}$$

Where:

$\mathbf{q_z}$ = velocity pressure at height z above ground (in PSF)
$\mathbf{K_z}$ = exposure coefficient at height z above ground*
$\mathbf{K_{zt}}$ = topographic factor (use this factor as 1.0 for flat terrain)
$\mathbf{K_d}$ = wind directionality factor**
$\mathbf{V}$ = basic wind speed in MPH
$\mathbf{I}$ = importance factor (use I = 1.0 for residential construction).

The ASCE recommends the use of the numerical coefficient 0.00256 in absence of a better one where better climatic data may be available.
* This factor is dependent on height above ground and the exposure category.
** The directionality factor can be taken from ASCE Table 6-6. We recommend 0.85.

One last comment on this matter: when the meteorologists refer to the "maximum sustained wind speed" they mean wind velocity at the international standard height of 10 meters (32.8 feet) above ground. The reason of this being so chosen is because at that height there are fewer obstructions to impede free air flow. However, what is felt on the ground surface is a lesser velocity as they are affected by the obstructions, such as buildings, chimneys, bridges, towers and forests commonly on the surface.

In our example, the rooftop will be at about a height of 19 feet above grade where the actual wind velocity is close to 87% as compared to that of the standard height of 10 meters as referred to by the meteorologists' measure of maximum sustained winds. Therefore, in the numerical example and wherever else necessary, we will adjust our design wind speed accordingly.

The subject design prototype is a fully "enclosed" structure with substantially protected openings. Wind pressures will be assumed to come from any horizontal direction and acting normally to any given surface under analysis. No decrease in wind loads will be made for the effect of shielding by other larger structures in the vicinity.

5.0 DESCRIPTION OF THE PROTOTYPE HOUSE

We have chosen an ordinary 2,120 square feet compact and self-contained house with a 40 x 53 ft. footprint layout (see Figure 5.1) and have added a few features to make it tornado resistant. First, we took the regular hollow concrete block exterior bearing walls and turned it into solid reinforced concrete masonry bearing walls. Secondly, we added a cross shaped set of interior bearing/shear walls to increase the lateral strength of the system. Thirdly, we replaced the traditional wood truss, sheathing and shingle roof with a poured in place reinforced concrete slab with a pitch corresponding to a base angle $\theta = 26°$.

The roof pitch is important enough to justify a pause here. While the base angle could be built anywhere between 10 to 45 degrees, the roof configuration itself has a considerable impact on the way the structure interacts with the wind; as the angle increases the more the wind gusts get deflected upwards and sideways. The most effective angle lies in between 25 and 35 degrees, once passed that point the pitch starts to lose its advantages as the air turbulence is on the increase.

There is another impact point in connection with the roof pitch, large base angles may create large attic spaces up above, which may steadily increase construction costs. On the positive side however, this may present the opportunity of using such created spaces as storage attics, lofts, security vaults or additional bonus rooms.

Although we have chosen a relatively small floor plan with only two bedrooms, two bathrooms and an interior single car garage, the house is totally expandable in both directions in order to accommodate the needs of the architect and/or the user to a maximum size of about 5,000 square feet, for as long as the shear wall layout concept and its two-way continuity is maintained as illustrated on the accompanying details and figures.

It is fair to say here that just because a house is made tornado resistant; it does not mean it has to look like a bunker. The enclosed Figure 5.2 shows an elevation of the proposed home which looks like any house down the road. We are sure that your chosen architect could do wonders to improve on the enclosed design.

The roof shown on said figure is what some of us call a “Bermuda” type roof. It is basically a cement mortar application consisting of a mix of 1 part of Portland cement and 6 parts of coarse river sand with added water to a consistency of a paste. The mix is applied to the concrete roof the day right after the pouring, with an average thickness of one inch. Straight edges or reglets are used to maintain constant thickness, spacing and alignment as shown on the elevation. The described roofing application should be maintained moist by using either a constant water mist or applied wet burlaps for a period of a week. After the mortared roofing and the reinforced concrete slab directly underneath have been adequately cured for a period of six weeks, two coatings of white waterproofing paint are applied and then the roofing job is complete. True that the described job is labor intensive, but the results are not only a tornado resistant and watertight roof structure, but an assembly that will last over one-hundred years with a minimum of maintenance during its service life.

When it comes to the piggy-back roof above the main entrance, there are two direct choices, the first one is to build it out of reinforced concrete as part and the same as the main roof, which we highly recommend, or to build it out of wood rafters and plywood sheathing as a break-away assembly designed to fail when winds reach a speed of 150 MPH.

Inasmuch as the enclosed design is based on the forces generated by tornadic winds, it must be kept in mind the fact that tornadoes sometimes may be part of a larger hurricane main event, and therefore flooding may also be part of such a disruptive weather, for that reason we recommend that the house floor elevation be raised to at least one foot above the FEMA anticipated 100 year maximum flood level.

Since a house built as proposed in this course was not thought as having an attic space, in its place we recommend a secondary cross-shaped reinforced concrete slab and dropped ceiling across from the kitchen to the main bathroom and from the front door to the rear garage. This is proposed in order to make room for the air conditioning ductwork, plumbing, forced ventilation, electrical and other necessary mechanical equipment and hardware. Figure 5.3 depicts the area in question with an access from the garage, a long term food storage room, and the necessary floor penetrations for HVAC (heating, ventilating and air conditioning), exhaust fan from the kitchen and plumbing vent pipes as applicable.

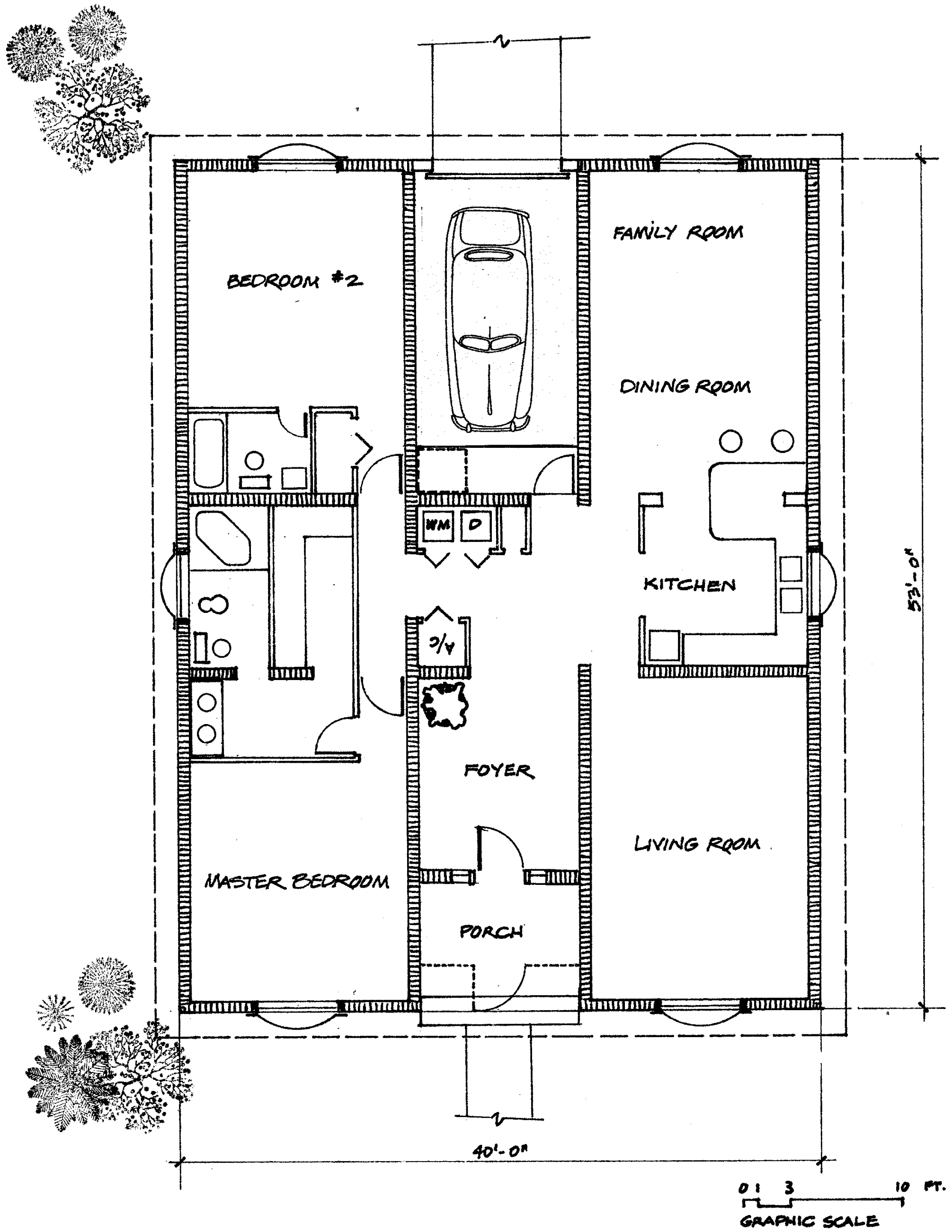
Although energy conservation is not part of the scope of this course, for those who may wonder of what to do about it, urethane insulation is very effective and could be introduced as part of the main design scheme by spraying it to the underside of the main roof slab.

As it has been repeatedly affirmed “a chain is as strong as its weakest link”, the windows of a house are the weakest part of it, therefore, an effective protection of those exterior wall openings is paramount. We favor for the windows one of two methods: a) high-impact resistant poly-carbonate (better known as “Lexan™”) or b) accordion shutters (either manual or motor operated). Figure 5.4 depicts a Lexan™ spherical dome (as Alternative A) installed on the outside of a typical standard window. Said dome is permanently fastened to the rough buck on the opening as it is not intended to be removed or operated. Since windows generally serve a dual purpose by allowing both, light and air flow, such solution may be objected by some code enforcers; in such case, Alternate B shall then be implemented.

Figure 5.5 describes said Alternate B with the accordion shutter, or “folding shutter” as called by the manufacturer, who affirms that their product has been successfully tested and proven “to withstand winds exceeding 230 MPH speed”. In such case, little changes and modifications could be made to improve its performance to match the specified tornado’s wind speed. Figure 5.6 depicts an isometric view of the manually operated folding shutter as it would appear when fully assembled and installed.

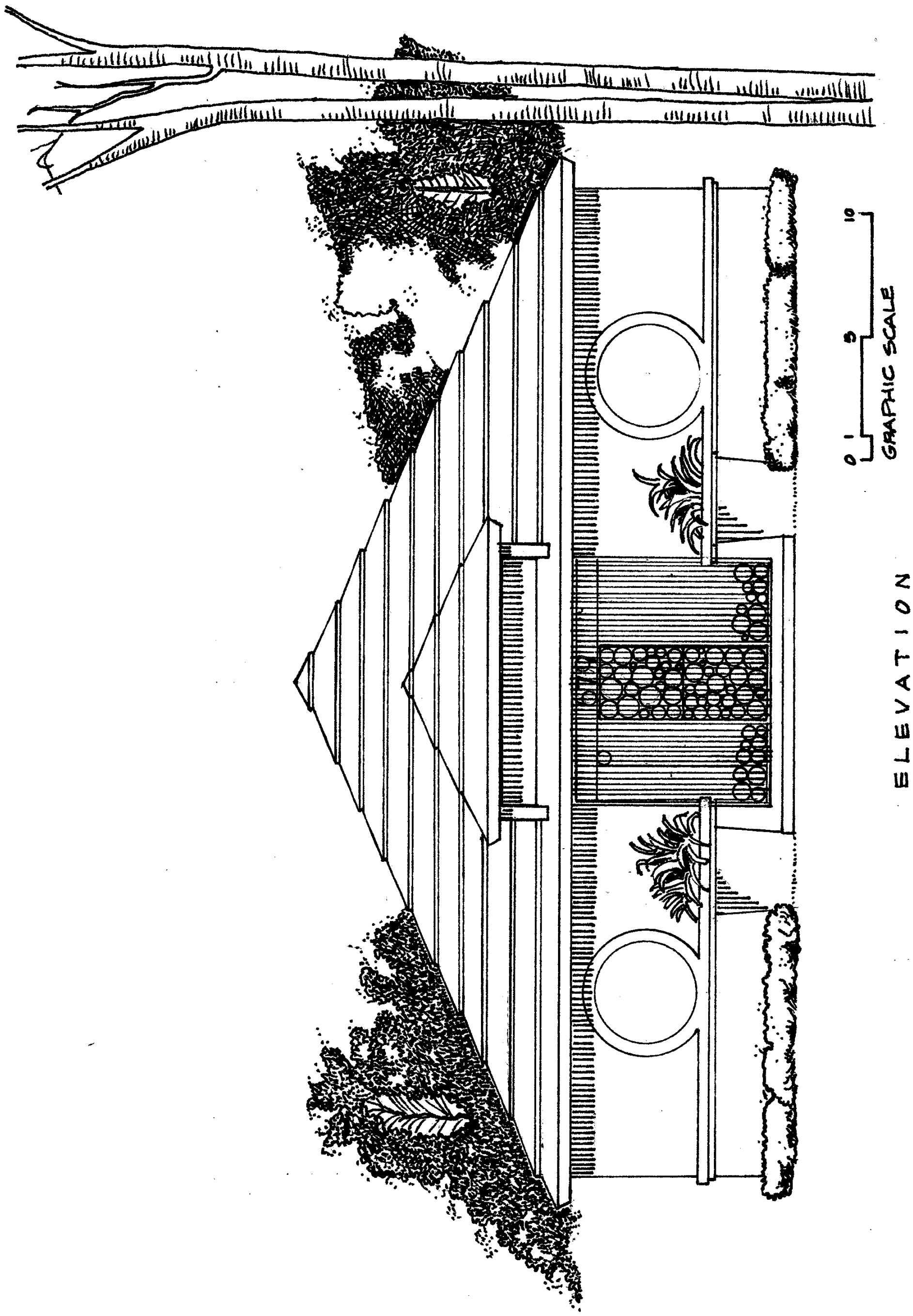
For the main door we have conceived an iron grille-work to trap large flying objects and also as a security feature. Last but not least, the 8 ft. wide garage door on the opposite end of the entrance door must be designed and installed to withstand the same positive and negative pressures as the contiguous exterior walls.

Lastly, Figure 5.7 shows a cut across the house which should complete the vision of the general design concept and answer any questions that may have been left behind in the above description.



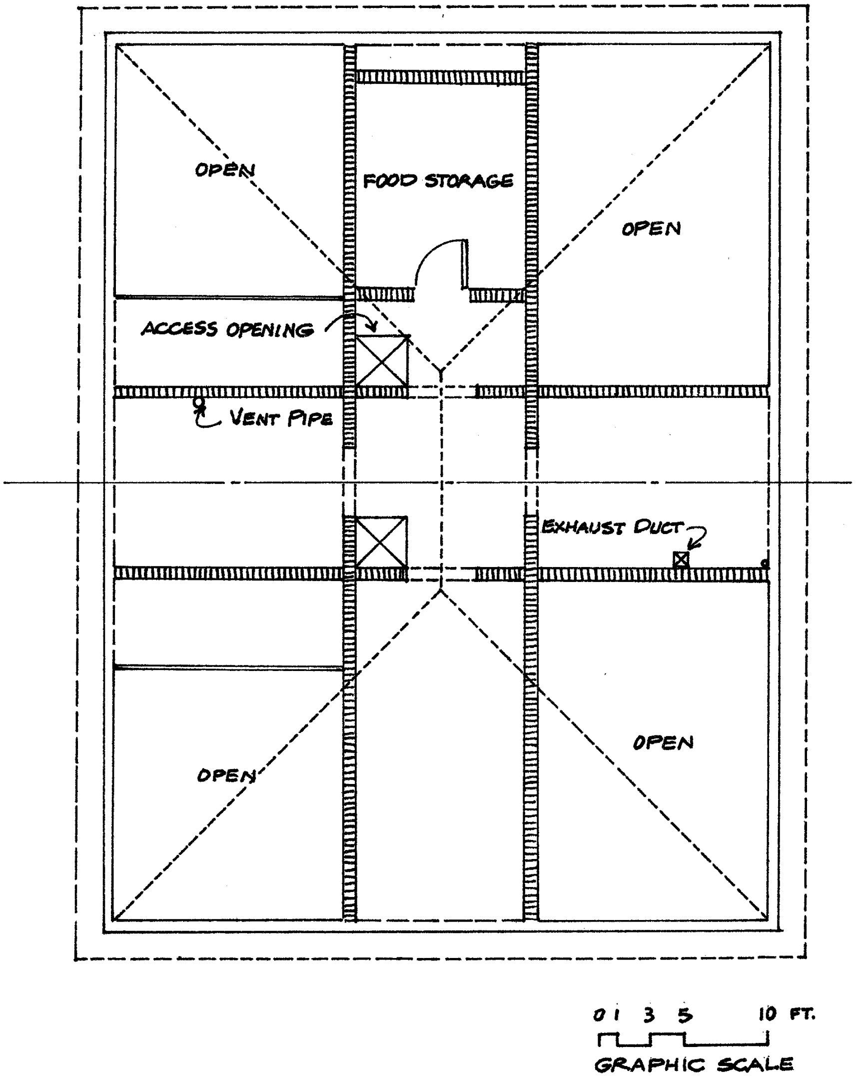
FLOOR PLAN

FIGURE 5.1

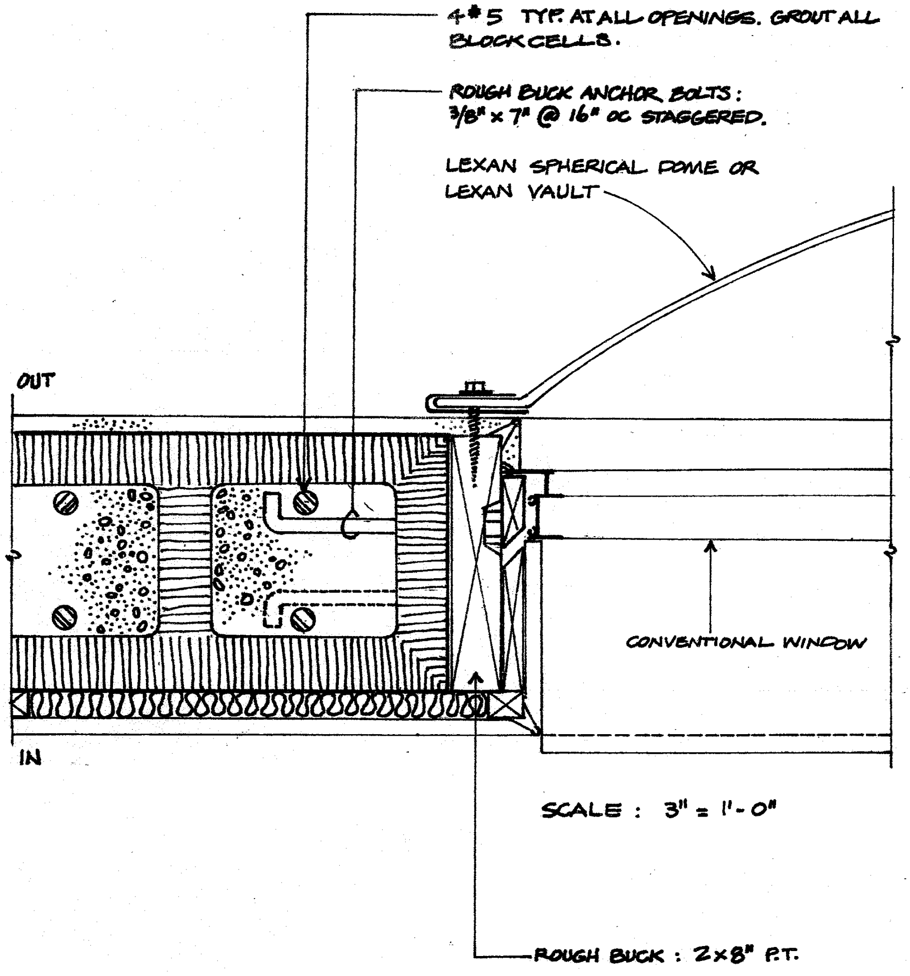


ELEVATION

FIGURE 5.2

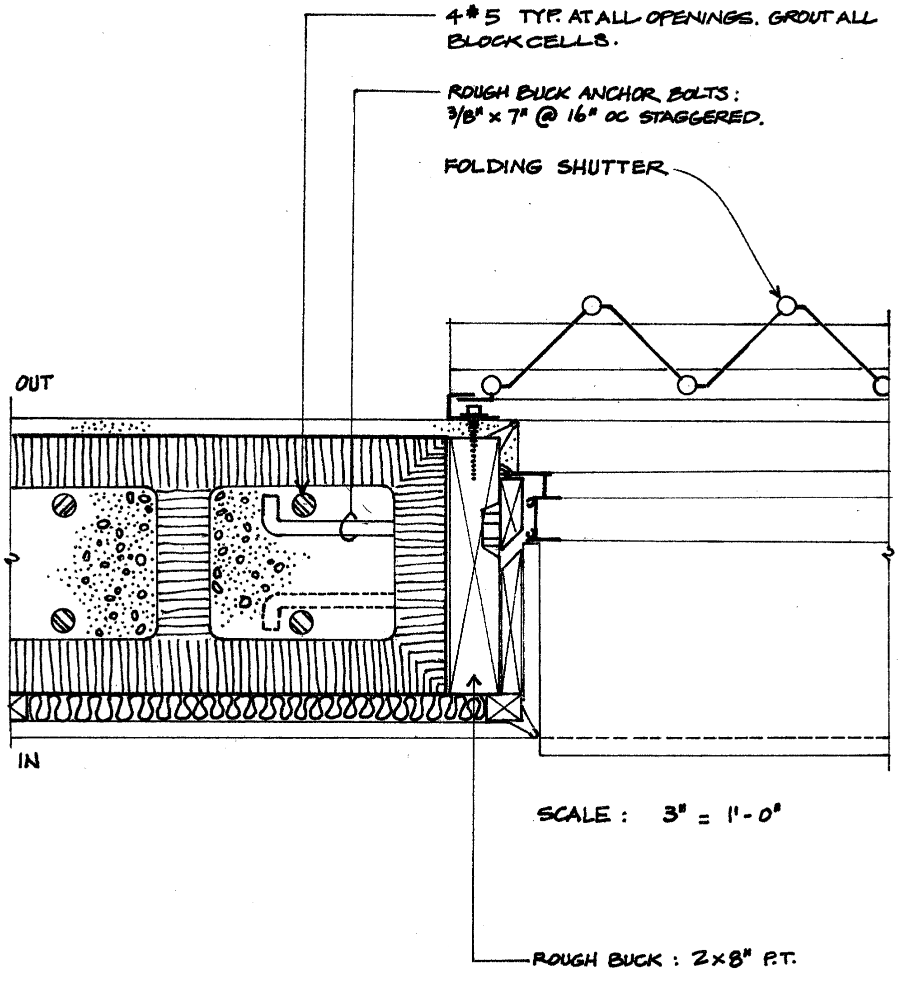


UPPER LEVEL
FIGURE 5.3



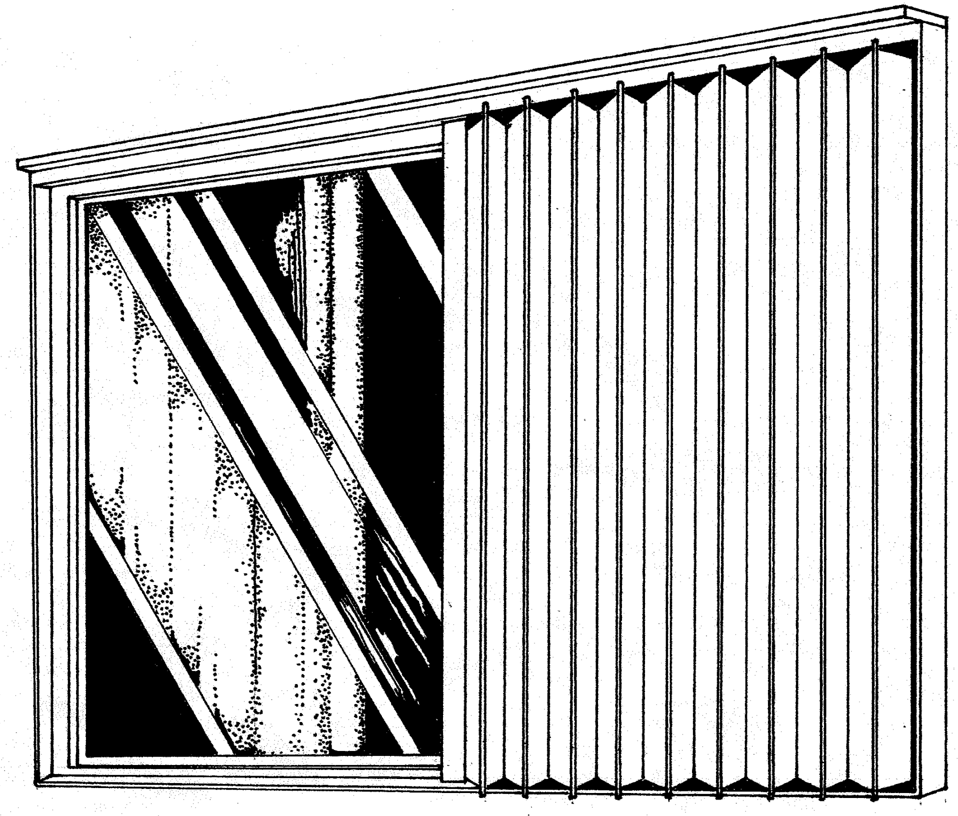
WINDOW PROTECTION -ALTERNATE A

FIGURE 5.4



WINDOW PROTECTION - ALTERNATE B

FIGURE 5.5



FOLDING SHUTTER

FIGURE 5.6

CROSS SECTION OF THE PROTOTYPE HOUSE

FIGURE 5.7

6.0 FOUNDATION: MONOLITHIC SLAB vs. CONCENTRIC FOOTINGS

For sixty years we have seen the popularity of the monolithic slab foundation grow amongst builders and engineers as a choice of convenience. It certainly is an easier, convenient and a more economic form of foundation, however, from the mere point of view of foundation engineering is a senseless anomaly which becomes apparent when the engineer tries to rationalize it and put it down in a comprehensive mathematical format.

As you read this paragraph, please closely follow the details on Figure 6.1 for a better understanding. Would the approach of an elastic slab foundation design be better or rather a rigid foundation on an elastic media (whatever is your take) work in this case? Would the actual width of the foundation wall in contact with the soil be enough bearing? If not, what extended width of the slab should be considered to satisfy the soil bearing requirements, would you say 4 times the slab thickness plus the width of the foundation wall (4t+b) would be enough? Stretching the speculation even further, if the design engineer added the bearing capacity at the base plus the slab shear strength, would that work? If so, would they actually work together in synchronicity or the soil under the base would have to fail first for the concrete shear strength to play its role? As you may realize, the so popular solution is filled with uncertainties.

We could continue asking ourselves questions on end with no convincing answers. In fact, if we decide to ignore the upper slab (which would be a denial of reality) as part of the bearing area and just use the base as the sole source of support, we will find that the more we widen the base the more eccentricity is brought up into the equation, and the more we widen the foundation wall the worse it would be.

While you are still looking at Figure 6.1, let us review its contents in more detail: Graphic marked “a” attempts to show an approximate representation of the isobaric curves (lines connecting points of equal soil pressure) of the *pressure bulb* for an ideal sandy soil. Most of those points have been either calculated using empirical formulas, interpolated or extrapolated from reliable charts. The reason the bulb is not concentric with the line of application of the load has to do with its eccentricity about the assumed engaged portion of the foundation slab.

Graphic “b” shows in contrast, the concentric footing bearing on natural or compacted sand, with its perfectly crisp and symmetric bulb as backed up by over 150 years of accumulated field experience and foundation engineering scientific data.

Lastly, Graphic marked “c” goes back to the monolithic slab foundation as is currently used in Florida, Georgia and some other areas of the country. This time we will use it to work out a numerical example based on some more assumptions which at the same time will bring some interesting findings. One question that many engineers ask of others or themselves is: how much slab width should be taken to figure out the maximum bearing stress? This is our preferred answer: 4t (four times the slab thickness), which we have borrowed from the *double T* existing and abundant experimental design data.

There is one more assumption that is necessary for the above concept to be acceptable; as the load P increases as the structure's erection progresses, part of such load will propagate down the foundation wall and the rest will be transmitted as a bending moment through the *throat d* into the horizontal slab in a decreasing mode until it gets balanced out at point M. As Load P grows, so will its generated moment until a failure occurs and a crack develops as indicated. Theoretically, the maximum bearing stress at point O can only fully develop until there is a slab failure at point M.

If we assume a soil bearing capacity of 2,000 PSF as well as the following parameters:

Slab thickness t = 4", thus: d = 3"
Also, b = 8" and c = 4"
Then: b + c + 4t = 8 + 4 + 16 = 28" (2.33 ft)

The soil area under consideration would be: A = 1.0 x 2.33 = 2.33 sq. ft.
Assuming a triangular soil stress diagram (stretching from point O to the M line), the distance between the center of gravity to the load P centerline is: 5.33" (0.44 ft)

Therefore: $M_P = 0.44P$ (P being the unknown)

$I = 1/12 \times 1.0 \times 2.33^3 = 1.05\ ft_4$

Substituting the values for the terms in the traditional equation:

$f = P/A + Mc/I$

$2000 = P/2.33 + (0.44P)0.78/1.05 = 0.76P$

Therefore,

P = 2000/0.76 = 2,632 lbs/ft (including the foundation weight).

Meaning that under the assumed conditions as described above, the maximum carrying capacity of the slab foundation, including its own weight, would be 2,632 pounds per linear foot.

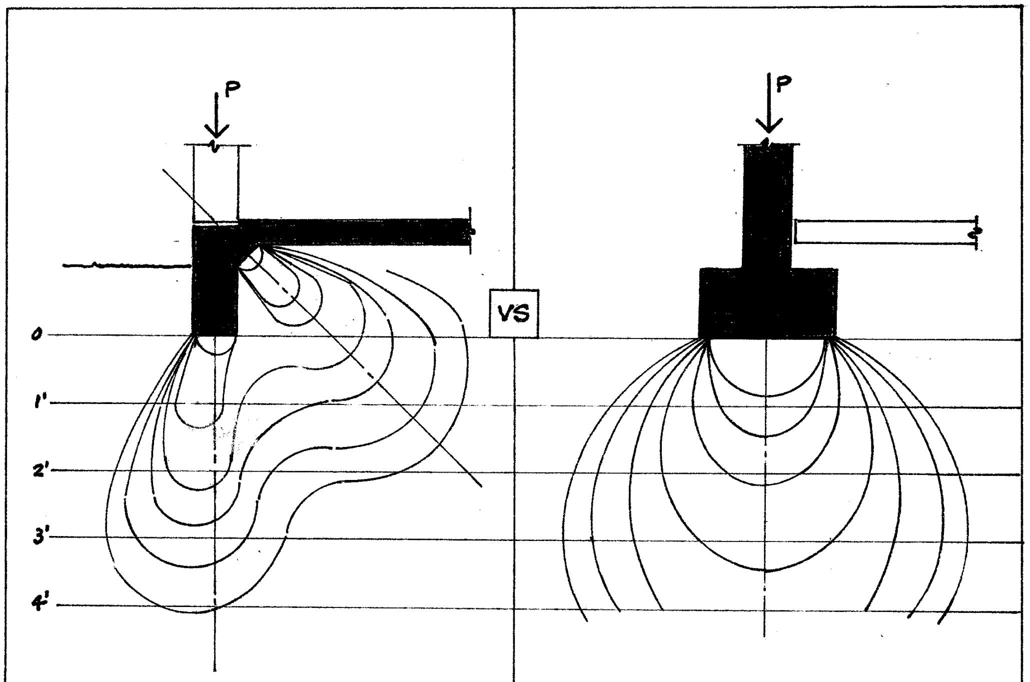
Still referring to Figure 6.1(c), in order for the above considerations to have any value, there are two more items that need to be emphasized, the first is that the *throat d* must be at least 5 inches in thickness, and the second one, that a corner bar (marked A) be added and sized accordingly depending on the moment at the throat.

We have repeatedly said in some other courses, that concrete has the propensity to crack and such cracking is basically dependent on two main causes: shrinkage and changes in temperature. However, when it comes to monolithic foundations there is one more important cause to consider: compaction, or rather the lack of it. Even when the builder makes a conscious effort to compact the soil base, which is not often the case, there comes the plumber, the electrician and the mechanical man and with little regard dig up the ground all over again to install their hardware, thus leaving behind disturbed soil and air pockets that a year later or less, will be the cause of undesirable and unsightly cracks.

Lastly, as the monolithic slab foundation is widely used in the states of Florida and Georgia, there is this loose modality of providing as the only bar reinforcement normally consisting of 2 #5's on the perimeter foundation wall and to leave the rest of the slab to mere fate and some random fibers (which ultimately end up failing) added by the batching plants to provide "safeguards" against cracks.

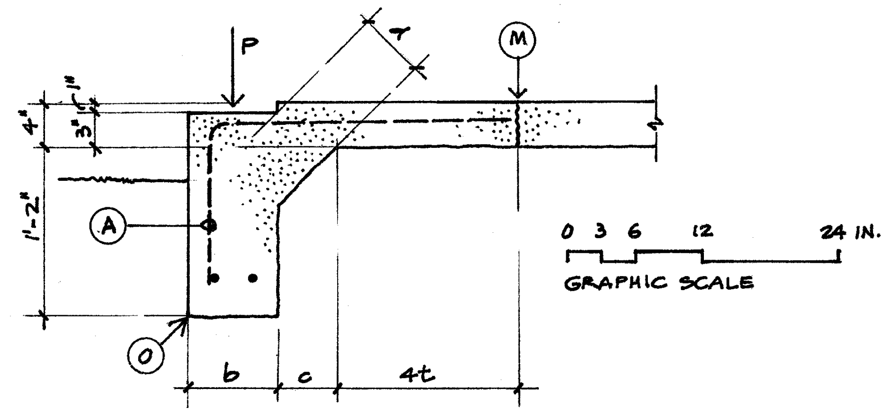
Again, while the monolithic slab foundation method may be a suitable solution for application to the many wood frame residential structures, however, it does not belong as part of a serious and responsible reinforced masonry methodology or any other field of heavy construction application.

As the readers may already suspect, the monolithic slab is not one of our favorites. In fact, we recommend that it should not to be used at all in tornado resistant designs. We instead highly favor the traditional concentric (stem) footings; the design principle is clear, simple, proven and dependable. Further, the loading is as concentric as we should wish it to be.



MONOLITHIC SLAB FOUNDATION
(a)

CONCENTRIC FOOTING
(b)



SLAB FOUNDATION DETAIL
(c)

FIGURE 6.1

7.0 SAMPLE CALCULATIONS

The parameters we will be using are as follows:

Enclosed Structure Type.
Height above ground: $z = 20$ ft.

Our prototype house is ideally located on a plot of flat terrain in the proximity to the coastal areas and with an exposure designated as a C category.

Internal Pressure Coefficient: 0.18
$a = 10\%$ of total width, $0.10 \times 40 = 4$ ft
$K_z = 0.90$
$K_{zt} = 1.0$
$K_d = 0.85$
$I = 1.0$
$V = 250$ MPH, $V^2 = 62{,}500$

Thus, going back to the wind pressure formula displayed in Section 4.0:

$q_z = 0.00256 \times 0.90 \times 1.0 \times 0.85 \times 62{,}500 \times 1.0 = 122.4$, we will use 123 PSF

In these sample computations we will not use the prescribed dynamic factor in the designing of components and have that on our side as an added safety factor.

Base angle: $\theta = 26^\circ$
$\sin \theta = 0.438$
$\cos \theta = 0.899$
$\tan \theta = 0.488$

Roof Loads (DL + LL):
Live Load……………………………………………20 PSF
Dead Loads: 6” concrete slab 75 PSF
1” cement finish 12 “ 87 “ 107 PSF

Floor Loads (DL + LL):
Live Load……………………………………………..40 PSF
Dead Loads: 5” concrete slab 62 PSF
Sprayed ceiling fin. 2 “ 64 “ 104 PSF

Dead Weight
Footings: (186+182)(2)(145)………………………………………106,720 lbs
Walls: (186+134)(9)(97)……………………………………………279,360
(900)(97)……………………………………………………87,300
Overhangs: (186)(1.50)(145)…………………………………………..40,455
Floor Slab……………………………………………………………..85,420

Upper Slab: (920)(0.42)145…………………………………………..56,028
Roof Slab: (53x40)(0.50)(1/0.899)(145)……………………………170,968
Roof Finish: (56x43)(1/0.899)(12)…………………………………..32,142

Total Dead Weight…………………………………………………871,385 lbs

Up-lift Force
(2120)(146) + (279)(246)…………………………………………..378,154 lbs

Up-lift Safety Factor: **F_s = 871.39/378.15 = 2.30**

The roof structure will be treated, rather than as a folded plate, but as a series of continuous two-way slabs. For continuation please follow up on the contents of Figure 7.1.

The applicable load distribution factors are as indicated on the table below:

Case #	Condition	S_x (ft)	S_y (ft)	Ratio	q_x	q_y
A	1	20.50	14.33	1.43	0.20	0.80
B	2	20.50	10.67	1.92	0.10	0.90
C	2	14.33	10.67	1.34	0.41	0.59
D	3	10.67	10.67	1.00	0.50	0.50

Typical Overhang Condition:

Gravity Loads: (DL+LL) = 107 PSF
-M = ½ x (107+50) x 1.83 x 1.83 = 263 lb-ft $f_{c'}$ = 3,000 PSI f_y = 60,000 PSI

A_s = (263 x 12)/273,312 = 0.0115 sq. in. less than A_{smin}. = 0.15 sq. in. = #4 @ 16” oc

(DL+Wind) = 246 – (75+50) = 121 PSF

+M = ½ x 121 x 3.35 = 203 lb-ft (minimum reinforcing applies).

Although they are not very consequential, we took some sample slab strips to verify the moments generated by the gravity loads (DL+LL). On Figure 7.2 we show the iterative steps of a moment distribution to determine the magnitude of the negative moments on the interior supports, for that purpose we will need the directional share of the loads, which are:

107 x 0.80 = 86 PLF for the end spans and,
107 x 0.90 = 96 PLF for the center span

In the same manner, we will also need the fixed-end-moments (FEM) for the iteration:

-M = 0.125 x 86 x 14.33 x 14.33 = 2,208 ft-lb for the end spans and,
-M = 0.083 x 96 x 10.67 x 10.67 = 911 ft-lb for the center span

With that information at hand, we can proceed to Figure 7.2. The resulting negative moment $-M_B$ was determined as 1,428 lb-ft. for the combination of DL+LL and 1,106 lb-ft for –DL+W.

For a slab's total thickness of: t = 6" and an effective depth of: d = 5":

A_s = 17.14/105.12 = 0.163 sq. in. say #4 @ 12" on centers (top and bottom)

On the other hand, a temperature reinforcing of:

A_t = 0.0025 x 5 x 12 = 0.15 sq. in. #3 @ 9" on centers

In the same Figure 7.2 we show wall vertical reinforcement as #4 @ 16" oc (both faces) which came from a wind moment:

$+M_w$ = 0.125 x 145 x 81 = 1,468 lb-ft

For a wall thickness: t = 7.5" and d = 5.5"

A_s = 17.62/115.63 = 0.152 sq. in. #4 @ 16" on centers

For the window opening as shown on Figures 5.4 and 5.5, we took a total wind force of: F = 2,903 lbs applied to the protective assembly. Using A307 3/8"steel bolts with a working shear capacity of 10,000 PSI,

A_v = 2,903/10,000 = 0.29 sq in.

Although a 3/8" bolt has a nominal area of 0.11 sq. in., but when adjusted for threading loss, the root area is reduced to 0.068 sq. in. Therefore, the minimum number of bolts used per opening should not be any less than:

n = 0.29/0.068 = 4.26 say 5 bolts.

In our analysis we did not give any consideration to snow loads, however, those of you who are in geographic areas subject to that type of precipitation should consider such loads as part of your work. The International Building Code is very detailed on that matter and provides on its Section 1608 the applicable superimposed loads for every region of the country.

There is one last item that needs to be covered as we deal with this subject of tornado wind design, and that is:

TORSION

Although there are more effective and efficient ways to add strength and stiffness to the proposed house floor plan, such as those shown in Figures 7.3(a) and (b), however, those schemes would not compatible with the space use and the traffic flow in the normal house. That is why we compromised with the proposed configuration on Figure 7.3(c).

As compared to the spread of a typical hurricane wind pattern, tornadoes are relatively small twisting air masses which can range from one hundred to five hundred feet in diameter. On the smaller diameter side, they will produce torsional moments in any structure or object on their path. Consequently, we will now have a look into that type of effect:

Our calculations show the following moments of inertia relating to the prototype structure:

Moment of inertia about axis x-x: $I_x = 68{,}994\ ft^4$
Moment of Inertia about axis y-y: $I_y = 42{,}366$
Polar moment of inertia: $J = 111{,}360$

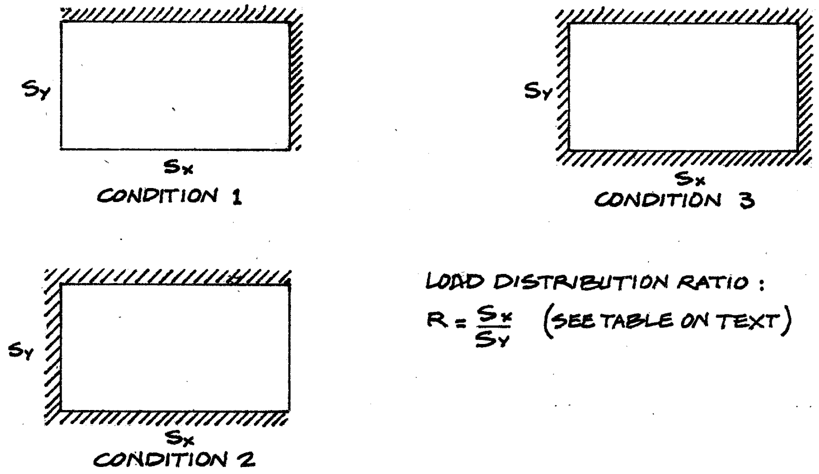
Total wall base area: 243.90 sq. ft. = 35,122 sq. in.

Base shear: V = 145 x 807 = 117,015 lbs

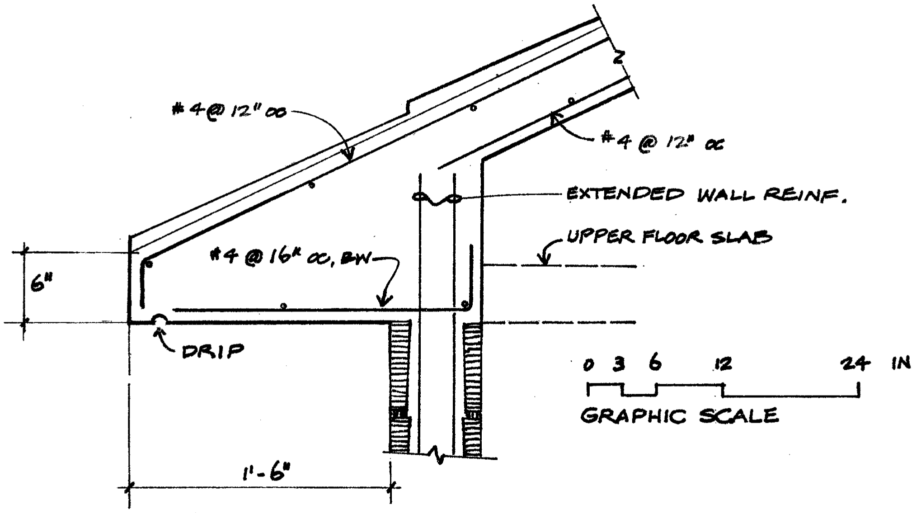
Bending shear stress: v = 117,015/35,122 = 3.33 PSI (negligible)

P = 871,385 lbs A = 35,122 sq. in. M_t = 2,067,088 lb-ft

Torsional shear stress: f_v = 24.81 + 6.78 = 31.6 PSI OK

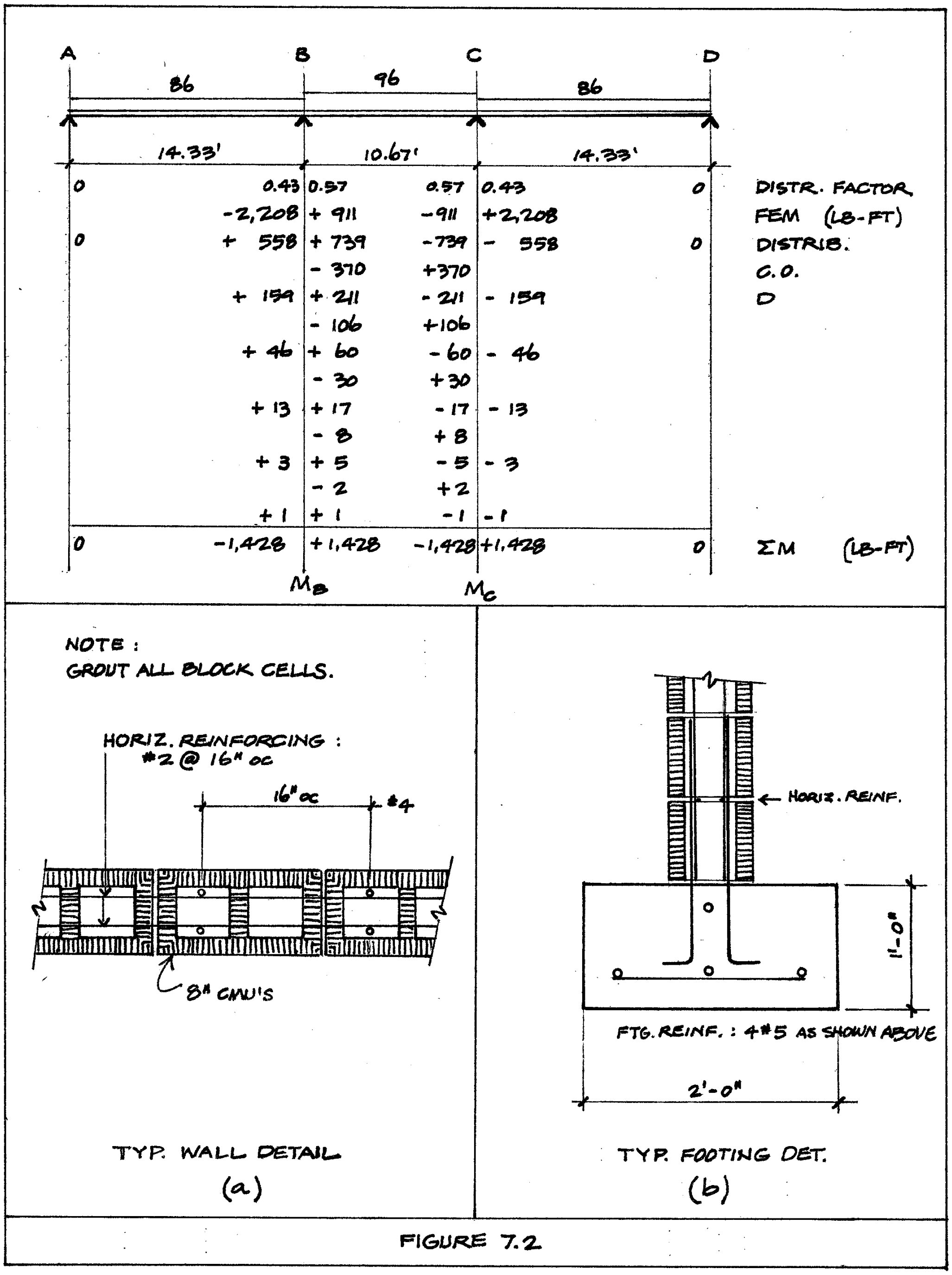


TWO-WAY ROOF SLAB CONDITIONS
(a)



TYPICAL ROOF OVERHANG
(b)

FIGURE 7.1



A	B		C		D	
0	0.43	0.57	0.57	0.43	0	DISTR. FACTOR
	-2,208	+ 911	-911	+2,208		FEM (LB-FT)
0	+ 558	+ 739	-739	- 558	0	DISTRIB.
		- 370	+370			C.O.
	+ 159	+ 211	- 211	- 159		D
		- 106	+106			
	+ 46	+ 60	- 60	- 46		
		- 30	+30			
	+ 13	+ 17	- 17	- 13		
		- 8	+ 8			
	+ 3	+ 5	- 5	- 3		
		- 2	+ 2			
	+ 1	+ 1	- 1	- 1		
0	-1,428	+1,428	-1,428	+1,428	0	ΣM (LB-FT)

FIGURE 7.2

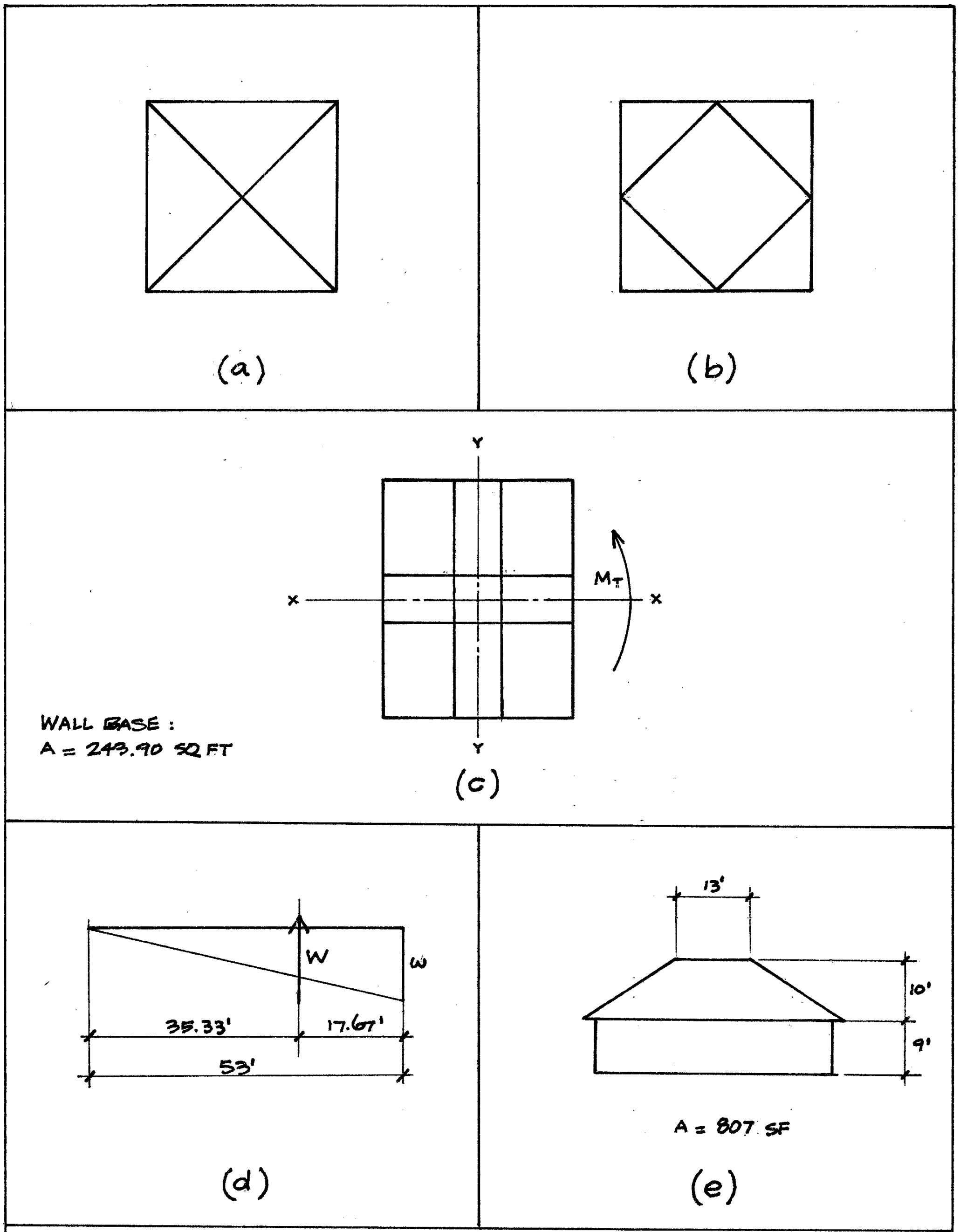

(a)
(b)
Y
X
M_T
X
Y
WALL BASE :
A = 243.90 SQ FT
(c)
W
ω
35.33'
17.67'
53'
(d)
13'
10'
9'
A = 807 SF
(e)

FIGURE 7.3

8.0 DISCUSSION

We have seen how, by using ordinary logic and known engineering principles, it is possible to design and build houses which are safe and resistant to tornadoes and therefore provide a safe place to live for our families with the certainty that they will awake tomorrow and find themselves with a sound roof above their heads, instead of the dreaded scenario of being blown away and perhaps killed in an event that could had been prevented.

To answer the question asked by one of our readers: why masonry walls? In fact, there is no reason why we could not use poured-in-place concrete walls, however, considering the reality that formwork is expensive and may constitute as high as fifty percent of the total cost of any structural concrete frame, we have proposed the use of masonry walls for the obvious reason of saving some costs. In addition, a masonry wall which is fully grouted and properly reinforced, both vertically and horizontally, may come as a very close second to a reinforced concrete wall.

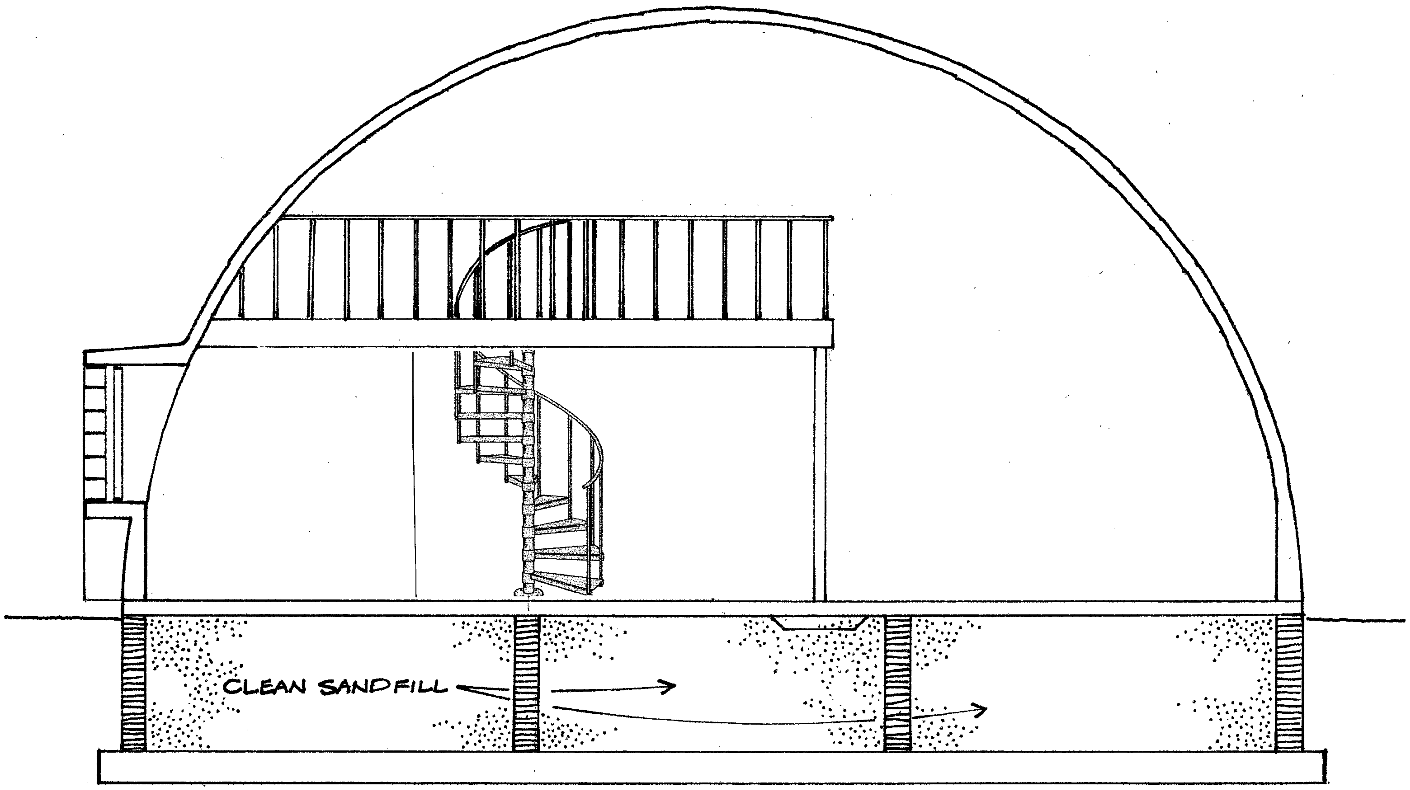
In retrospect and after reviewing our own calculations and the different conditions and stresses generated as consequence of the 250 MPH winds, such as direct wind pressure bending, base shear, torque, overturning and uplift, we found uplift to be the one to be reckoned with. Therefore, for higher winds than those herein considered we must recommend the multi-chambered sand-filled foundation described ahead as the most practical and economical solution.

As indicated before, we limited our sample calculations to a wind velocity of 250 MPH because ninety-nine percent (99%) of all tornadoes produce winds of that velocity or below, however, there is no reason why our design could not have provided for all possibilities all the way up to 100%. In fact, and we have mentioned this before in many of our statements by different avenues, concrete domes are virtually indestructible structures. With little additional cost, reinforced concrete domes can be designed and built to resist winds well in excess of 300 MPH and even air blasts produced by military weapons with a resulting *peak overpressure* in the double digits (PSI). It is a well documented fact that in 1944 German domes in Berlin stood up to allied bombing, in the same manner; in 1945 the only structure left standing in the area near ground zero in Hiroshima was a concrete dome. However, when it comes to domes for residential application, there are **two important considerations** that must be taken into account to further preserve their structural integrity and the safety of their occupants as well, those two are: a) opening protection and b) adequate ballast against uplift forces.

When it comes to opening protection we have repeatedly described a few of the many solutions available, both within the text of this course as well as in a previous course of ours titled “Simplified Principles of Wind Analysis”. As a solution to providing a foundation adequate and economic enough to anchor the structure in such a way that is able to stand up-lift forces of any nature and magnitude, we have developed a detail as shown on the enclosed Figure 8.1. Although not shown on said figure, the exterior walls of the multi-chambered foundation need to be waterproofed with a tar coating to avoid water intrusion, and at the same time, they also need to be provided with weep holes to allow drainage for water gathered inside due to condensation, seepage or plumbing pipe leaks, if any.

We need to bear in mind that the dead weight of a regular residential dome is barely 50-60 PSF, while a Fujita F5 tornado can generate up-lift forces three to four times as large. Consequently, the solution will be found by providing a multi-chambered sand-filled foundation as shown on the figure, the rest is indeed self-explanatory.

There is one last comment about concrete domes; they are so structurally effective that small thicknesses may go a very long way. For instance, a concrete thickness of three (3) inches could be enough to cover the structural requirements of diameters up to 60 feet. However, if they were going to be used in active tornado areas, in order to protect the integrity of the structure against punctures caused by flying objects, a minimum thickness of four (4) inches as well as a minimum concrete compressive strength of 3,500 PSI should be specified.



MULTI-CHAMBERED FOUNDATION FOR TORNADO RESISTANT DOME
FIGURE 8.1

9.0 EPILOGUE

There will be plenty of detractors and lobbyists who will find reasons to adhere to their traditional objections and excuses to justify why we should not bother to look for ways to prevent the "unpreventable". In their opinion, wood, cardboard and paper houses are fine an inexpensive (or "competitive" as some prefer to call them) to provide for their needs of room and shelter. If they have such a poor luck that a tornado, or a hurricane for that matter, comes along their way and demolishes their houses to the ground, why worry, that is what they have insurance for. They will build brand new ones (built out of wood, cardboard and paper again) and in the process will stimulate the economy. It would not make any difference if the lives of the members of their own families and those of the community for that matter, were at risk.

It should be obvious to the reader as well to anyone who bothers to listen, of the fact that we need to rethink our priorities when it comes to the place we call home, otherwise we may prove the principle of "a man's home is his castle" to be another fallacious cliché.

We can rest assured that some architects will also join the bandwagon and argue that what we have proposed herein is too restrictive, expensive and inflexible. Although there may well be some truth to such assessments, however, that is one of the rules of life, you pay for what you get. Furthermore, in what should really be in their own defense, we must say, that it is precisely where the true qualities of talent, creativity and resourcefulness lie, to try our very best to find harmonious *form* within the unforgiving limitations of *function*.