A DESIGN OF AN AIR RAID SHELTER

Thesis for the Degree of B. S.
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John Walter Missall
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A DESIGN OF AN AIR RAID SHELTER

A Thesis Submitted to

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OF

AGRICULTURE AND APPLIED SCIENCE

by

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Candidate for the Degree
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It is intended to design a bomb shelter to withstand the penetrating and destructive effects of a demolition bomb. A demolition bomb is of the delayed action type where the bomb penetrates a considerable distance through the target before the charge within explodes.[1] This bomb has, and is, producing devastating effects on architectural structures by penetrating the walls, exploding, and causing internal pressures within the building therefore causing the walls to collapse.

Although human life should be preserved against any possible danger, I have disregarded the fact and simulated my shelter design to that of a drainage system. In the case of a drainage system, it is not designed to accomodate the maximum expected flow. It is far more inexpensive to build a system which will accomodate a substantially large flow which is not the maximum. When the maximum flood occurs, the system will be insufficient thus causing an overflow resulting in material damage to the surrounding area. From a practical standpoint, it has been deemed advisable to bear the damage costs rather than to pay an added initial cost to build a system which will accomodate the maximum flow.

My shelter design is paralleled to that of a sewer design in that it is not designed to withstand the maximum weight bomb.

Reasons for this statement are: Firstly, it is highly impractical to carry a bomb heavier than 1000 pounds for long distances because the carrier then has only one vulnerable power. When that one bomb is expended the effect of the carrier is gone. Secondly, in actual tests it has been determined that the area of destruction from a 1000 pound bomb is 380 sq. ft. If this same bomb weight is split up so the carrier has ten 100 pound bombs and drops them simultaneously, the area of destruction mounts to 885 sq, ft.[2] It can further be deduced that a bomb of such weight would mainly be used against a small concentrated, and highly important target. Thirdly, bomb shelters are not discernable from the air so such a target would be next to impossible to hit intentionally from the air. ---It is for these reasons that I have based my design on the action of a 500 pound bomb.

The design of a bomb shelter can be based on one of the three following methods.[3]

1. Bomb forces are replaced by equivalent static loads. In this case the already existing static equilibrium equations can be used.
2. Design on actual energy loads. In this case a thorough study would have to be made to determine the amount of explosive energy concrete can withstand.
3. Design by the use of strictly emperical formulas derived by forces expended on bomb shelters in England.

My design uses the first of these three methods. Besides being more tutored and acquainted with this style of design, a recent search through texts and pamphlets have led me to believe that my design would be just as good or even better than any derived by the use of Method number 3. Emperical formulas for shelter designs are merely static equations altered by assumptions. I am therefore doing the same thing except I am using assumptions of my own.

At the moment of impact, a bomb has a velocity which is mainly due to gravitational pull. The aircraft gives the projectile a horizontal velocity component when flying parallel to the ground. Any slight inclination to the ground will give the projectile an initial vertical component. ---Thus dive bombing. The following set of computations are presented to prove that the main factor in the design of a structure against a projectile with the speed of a bomb is shear. Using the knowledge that bombing planes usually fly at 10,000 ft. when dropping the projectiles, we can readilly assume that the vertical distance traveled by the bomb is 10,000 ft.[4]

v = velocity in ft./sec.
a = acceleration due to gravity
s = vertical distance of fall

$$v^2 = 2as$$
$$v^2 = 2(32)(10,000)$$
$$v^2 = 640,000$$

$$v = 800 \text{ ft./sec.}$$

Assume that a 500 pound bomb will penetrate a concrete slab 2 feet before exploding.[5]

x = depth of penetration
w = weight of bomb
F = static concentrated force of bomb
v = velocity upon impact (conservative estimate)
a = acceleration due to gravity

$$F = \frac{wv^2}{2ax}$$

$$F = \frac{500(1000)^2}{2(32)(2)}$$

$$F = 4{,}000{,}000\#$$

Concentrated force exerted on a concrete slab by a 500 pound bomb 4,000 kips.

Use:

f_c = 2000 p.s.i.
f_s = 30000 p.s.i.
u = 225 p.s.i.
v = 400 p.s.i. (with stirrups)
k = .4
j = .875
K = 348
p = 1.33%

Assume that slab is 6 ft. thick

Dead Load = 900 #/ft
Live Load = 4,000 kips

Neglect Dead Load

We cannot consider the bomb as a point concentrated force because of its diameter and the inclination of the bomb to the target surface. Thus the effective width of impact is taken here as 5 feet.

Shear $V = 4,000$ kips

$$\text{Min } d = \frac{V}{vjbw}$$

$$\text{Min } d = \frac{4,000,000}{135 \times \frac{7}{8} \times 5 \times 12}$$

Min d =47 ft.

Moments

$$\text{Min } d = \sqrt{\frac{M}{Rbw}}$$

$$\text{Min } d = \sqrt{\frac{5,400,000 \times 12}{(348)(12)(5)}} = 56''$$

Min d 5 ft.

It can easily be seen that the design must be calculated to accommodate shear stresses.

In actual tests it has been determined that if the negative and positive steel in the reinforcing of the slab is staggered, the effective width of the applied bomb force is increased to over ten feet. Also, if high strength steel and concrete is used so computations can be based using $v = 400$ p.s.i., a concrete slab 5 feet thick will provide ample protection from a 500 pound bomb.[6] Using this knowledge, I have designed my shelter using a 5 ft. slab roof of reinforced concrete. The steel and concrete dimensions are based on dead load criteria. This has been done because the high speed of the projectile will produce such instantaneous shock, that the resulting bending moment will be of negligible consequence. It must be noted that the main factor is to exclude the projectile from the inner portion of the structure. If the projectile cannot enter the shelter, there can be little harm from the blast as it will direct its energy to the path of least resistance. In this case the path of least resistance is the line which the projectile followed into the concrete slab.

It will be noticed in the drawing that the shelter is a virtual system of corridors. This is an additional protective measure. If a bomb falls into one part of the shelter, the inhabitants of the adjacent corridor will receive blast protection afforded by the wall.

DESIGN

A. Roof Slab

a. Short Span

Use 13 ft. clear span
$b = 12''$

$DL = 5 \times 150 = 750\ \#/\square'$

$w_s = 750 \times 12 = 9{,}000\ \#/ft.$

Design for continuous interior span because the resulting moment is numerically less.

$$M_s = \frac{1}{12} w l^2$$
$$M_s = \frac{1}{12}(12)(9000)(13)^2$$
$$M_s = 9000(169)$$
$$M_s = 1{,}521{,}000''\#$$

Use $f_s = 30{,}000$ p.s.i.
$f_c = 900$ p.s.i.
$n = 15$

$$k = \frac{1}{1 + \frac{f_s}{n f_c}}$$

$$k = \frac{1}{1 + \frac{30{,}000}{15(900)}}$$

$$k = \frac{135}{435} = .3105$$

$$j = 1 - \frac{k}{3} = 1 - \frac{.3105}{3} = .8965$$

$$M = \frac{f}{2} k b j d^2$$

$$M = \frac{900}{2}(.3105)(.8965)(12)(d)^2 = 1{,}521{,}000''\#$$

$$d^2 = \frac{1{,}521{,}000}{450(.3105)(.8965)(12)}$$

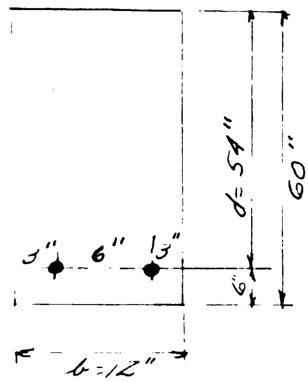
$$d^2 = 1{,}102$$

$$d = 33''$$

Use d = 54"

$$A_s = \frac{M}{f_s jd} \quad \frac{1,521,000}{30,000(.8865)(12)} = 1.05\,\square''$$

Use 2- $\frac{7}{8}''$ ϕ bars. (a = $1.20\,\square''$)

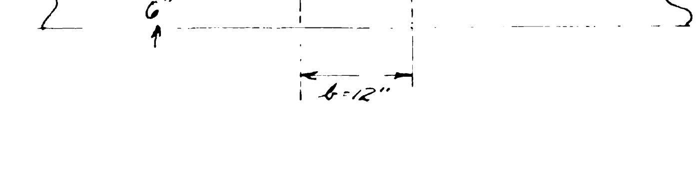


b. End Quarters

At end quarters the moment is reduced 50% but due to the need of protective steel throughout, the steel will be placed uniformly over the complete beam length.

c. Negative Steel

Steel should extend only to quarter points. It will however, be placed in the same manner as the positive steel except that it will be staggered to increase effective width of bomb contact.



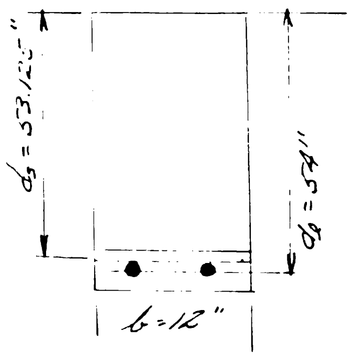
d. Long Span

Clear span = 13 ft.

w_l is the same as w_s = 9,000 pounds/ft.

$M = \frac{1}{12} w l^2$

$$M = \frac{9000(169)(12)}{12} = 1,521,000 "\#$$



$d_l = d_s - 7/8 - 53.125"$

The value of d_s was made much larger than required so the slight difference between d_l and d_s will not make much difference in the bending moments. Same steel will be used in long and short spans of the slab.

e. Maximum Shear Stress

$$v = \frac{.5\ V}{bjd}$$ Assume j = .92

$$v = \frac{.5(9000)}{12(53.125)(.92)}$$

v = 76.8 p.s.i. ← okay

Allowable = $.06(f_c)$ = .06(2000) = 120 P.S.I.

f. Bond

Allowable = 100 p.s.i.

$$u = \frac{V}{\Sigma_o jd}$$

$$u = \frac{.5(9000)}{5.5(.92)(53.\overline{1}25)}$$

$$u = 16.7 \text{ p.s.i.}$$ okay

B. Cross Beams

a. The beams are spaced 15 ft. ℄-℄. The beams are further assumed as 24" wide and 24" deep.

Slab weight to beam = 750(15)(13) = 146250 #/ft

Beam weight = 2(2)(150) = 600 #/ft

Total w = 146850 #/ft

Clear span = 13 ft.

Use 14 - 1" ϕ bars (A = 11.0 □")

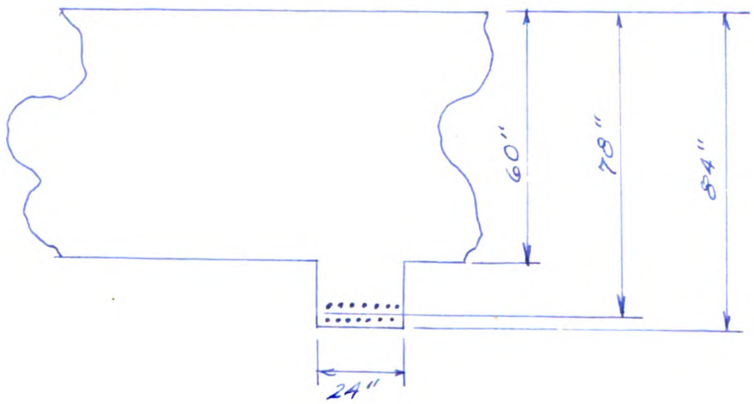
$$M = \frac{wl^2}{12}$$

$$M = \frac{146{,}850(12)(13)^2}{12}$$

$$M = 24{,}640{,}000 \text{ "\#}$$

Use d = 78"

Use b as $\frac{1}{4}$clear span = $\frac{13}{4}$ = 3.25' or 39"



b. Take Moments about N.A.

$$39(60)(x-30) = (78-x)(15)(11.0)$$

$$(2340)(x-30) = -165x + 12,870$$

$$2340x - 70,200 = -165x + 12,870$$

$$2,405x = 83,070$$

$$x = 30.1''$$

$kd = 30.1''$

$f_c = 900$ p.s.i.

$f_s = 30,000$ p.s.i.

$n = 15$

$$jd = d - \frac{kd}{3} = 78 - \frac{30.1}{3} = 61.7''$$

$$C = T = \frac{f}{2}bjd = \frac{900}{2}(24)(61.7) = 616,000\ \#$$

Resisting Moment $M_r = Cjd$

$$M_r = (616,000)(61.7)$$

$$M_r = 37,000,000\ ''\#$$

Resisting Moment is greater than Moment applied so members are designed correctly.

c. Check Shear

$$v = \frac{V}{bjd} = \frac{.5(146,850)}{24(61.7)} = 49.5 \text{ p.s.i.}$$

Allowable = 60 p.s.i.

d. Stirrups

Use $\frac{1}{2}''\ \phi$ stirrups. Also use shear obtained from above calculations, but call $v = 50$ p.s.i.

Max. spacing $= 3/4\ d = \frac{3(61.7)}{4} = 46.2"$

Min. spacing
find s

$$60 = 50 - \frac{2\ (.05)(16,000)}{24(s)}$$

$$(10)(s)(24) = 1600$$

$$s = \frac{1600}{240} = 6.68"$$

Space stirrups every six inches.

C. Wall Design

Since the upper 24" of the walls are in reality the beams just designed, the walls will also be made 24" thick. There is another reason for making them so thick and that has been mentioned in the introduction. The walls are to be designed as columns. The intersections of the walls will actually be columns and will be reinforced as such. The clear height inside the shelter will be ten feet so the columns are therefore taken as being ten feet high, and 24" square.

a. Weight to column

Roof weight	15x15x150x5	=	168,750 #
Beam weight	2 x 2 x 150x15	=	9,000 #
column weight	2x2x150x10	=	6,000 #
	Total P	=	183,750 #

In column design

Use: $f'_c = 2000$ p.s.i.

4" cover

2% vertical steel

$n = 15$

longitudinal bars and ties

$f_c = 400$ p.s.i.

$f_s = 16{,}000$ p.s.i.

core diam. = 24" - 8" = 16"

$$P = f_c A\left[1 + p(n-1)\right]$$

$$183{,}750 = 660A\left[1 + .02(15-1)\right]$$

$$A = \frac{183{,}750}{660(1.28)}$$

$$A = 218$$

$$d^2 = 218$$

$$d = 14.8''$$

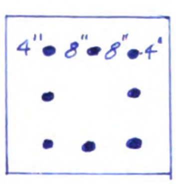
Check okay---d already assumed as 16"

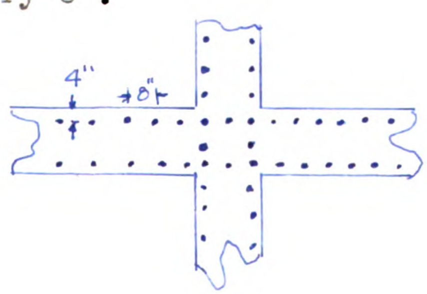
$$a_s = pA$$

$$a_s = .02(218) = 4.36\ \square''$$

Use 8-7/8" ϕ bars. ($A = 4.81\ \square''$)

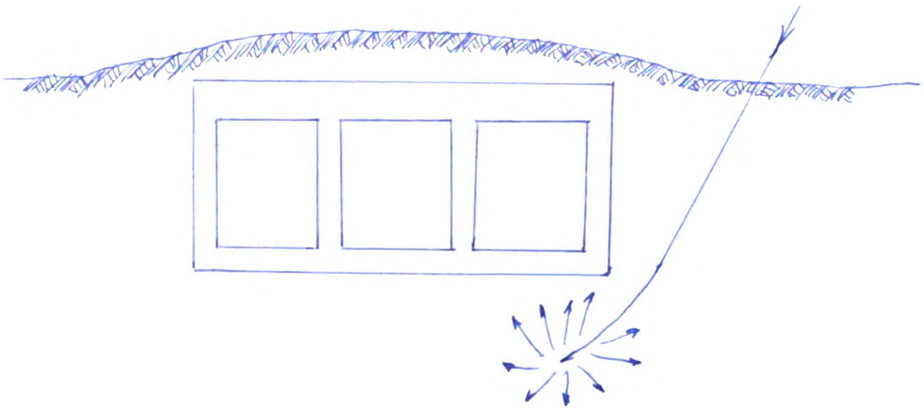
Build wall to conform with this column design. Use 3/8" ties and space them every 6"!

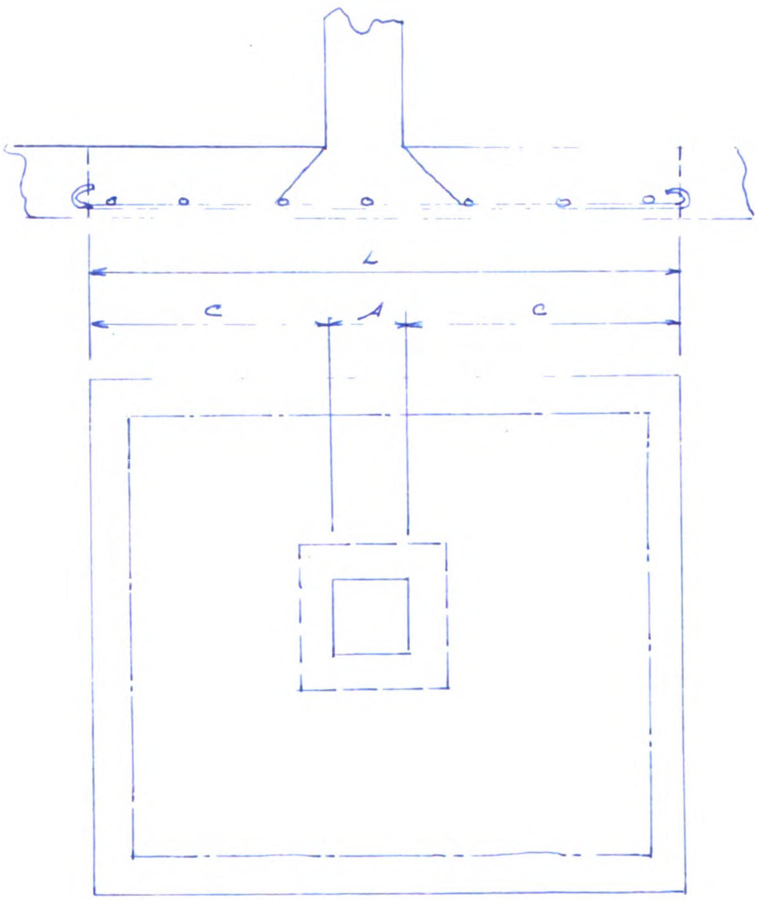




D. Flooring and Footing

Flooring will be assumed to be two feet thick to give ample protection from blasts as pictured below. This 2' slab will be designed so as to act as a suitable footing at the same time. Thus the footing will necessarily be 15 ft. square and 2 ft. thick.





Assume soil pressure = 4,000 pounds per sq. ft.

Load from column = 183,750 #

Load of footing = 67,500 #

Total = 251,250 #

a. Area of base = 225 □'

L = 15'

$$L = 2c + A$$

$$15 = 2c + 2$$

$$2c = 13$$

$$c = 6.5'$$

Net pressure

$$p = \frac{P}{A} = \frac{251,250}{225} = 1120 \;\#/□'$$

b. Moment

$$M = \frac{Pc^2}{2}(A + 1.2c)$$

$$M = \frac{12(1120)(6.5)^2}{2(144)}\left[24 + 1.2(6.5)(12)\right]$$

$$M = 560(42.2)\left[24 + 1.2(78.1)\right]$$

$$M = 560(44.22)\left[24 + 93.9\right]$$

$$M = 279,200 \;''\#$$

K = 160

$$d = \sqrt{\frac{M}{Kb}} = \sqrt{\frac{279,200}{160(12)}} \doteq \sqrt{145} = 12.1''$$

Call d = 16"

c. Check Punching Shear

$$V = 1120(225 - 2^2)$$

$$V = 1120(221) = 247,900\;\#$$

$$v = \frac{V}{bjd}$$

$$v = \frac{247,900}{15(12)(.875)16}$$

v = 98 p.s.i. ← okay

180 p.s.i. allowable with anchorage

d. Check Diagonal Shear

$$v = .03(f_c)$$

$$v = .03(2000)$$

v = 60 p.s.i.

$$v = 1120\left[225 - \frac{(56)^2}{144}\right]$$

$$v = 1120\ (225 - 21.8)$$

$$v = 250,020\ \#$$

$$d = \frac{V}{vjb} = \frac{250,020}{60(.875)(24-32)4} = 19.2''$$

Call d 20"

Revise footing to take care of diagonal shear.

e. Footing Steel

$$A_s = \frac{M}{f_s jd} = \frac{279,200}{18,000(.875)(20)} = .887^{\square''}$$

Use 8-3/8" ϕ bars. ($A = .88^{\square''}$)

f. Band Width

$$W = \tfrac{1}{2}(1 + A\ 2d)$$

$$W = \tfrac{1}{2}(12 \times 15 + 24 + 32)$$

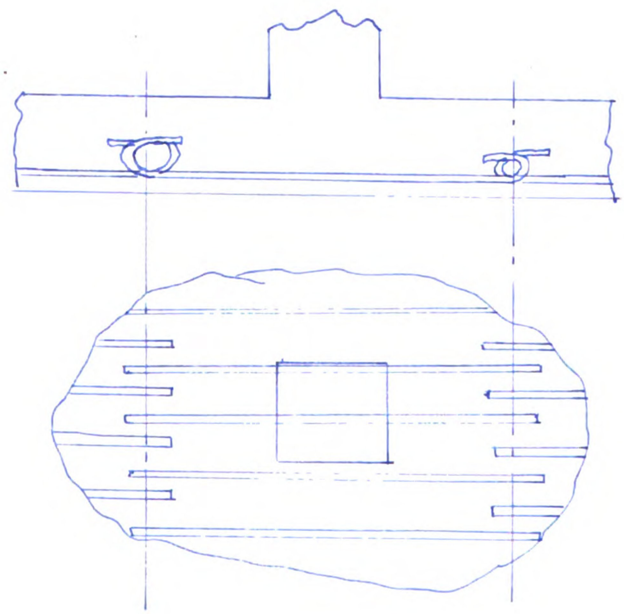
$$W = \tfrac{1}{2}(180 + 56)$$

$$W = 118''$$

Spacing:

$$s = \frac{118}{8} = 15'' \quad \text{℄} - \text{℄}$$

Use **15"** spacing of bars throughout flooring in both directions. The bars are 15'-6" long and are placed 20" deep to accomodate the "d" derived. Outside walls are reinforced with a 5" square mesh of $\frac{3}{4}$" thick bars. The mesh is placed 2" in from the wall faces.



It is very apparent that the design incorporates a high degree of leniency. In practically every member the dimensions were much in excess of that required. This apparent over-size should not be misunderstood. These were not due to laxity in computations, but rather to intended oversizes. It was sometimes difficult to proportion the parts so they would be larger and stronger than those called for in the initial calculations. This over-design was practiced to make some compensation for the live load effect of the bomb and the bending moment that it produced.

By considering the drawing, it will be noted that there are two outlets which may be used interchangeably as entrances or emergency exits. The decontamination center, being at the end of the first corridor, naturally suggests that its outside opening be used as the entrance. The partitions that enclose the decontamination center, and wash rooms are of a simple concrete construction. Studding and metal lath are the inner constituents of the wall. The doors and door casings are metal.

At the end of the first corridor and also at the end of the third corridor are lavatories. The second or middle corridor consists of benches and tables for rest purposes. The third corridor is devoted entirely to sleeping and casualty quarters. The room is outfitted with triple deck beds. A lavatory finishes the outlay of the third corridor.

The staircases for the two outlets will be noted in the drawing as consisting of two flights of wide stairs. An overhead concrete protective covering aids in keeping debris out of the doorway.

It can readily be seen that a larger shelter can easily be constructed by adding adjacent corridors to the existing shelter. The design can be of the same type as already standing.

Ventilation is accomplished by the use of 1 ft. square metal ducts. The duct is partitioned so there are two channels within. The lower channel conducts air into the chambers, while the upper chamber sucks the foul air out of the building. The outside connections to these ducts will extend from the bottom of the shelter to points about twenty feet distant from the shelter.

Water and sewer pipes leave and enter the shelter at an elevation lower than that of the floor of the shelter. The pipework connecting the various points within the shelter is all placed inside the shelter on the floor.

The electrical system consists of pipe conduits fastened to the walls on the inside. The incoming power line will also be conducted through the ground and enter through the floor.

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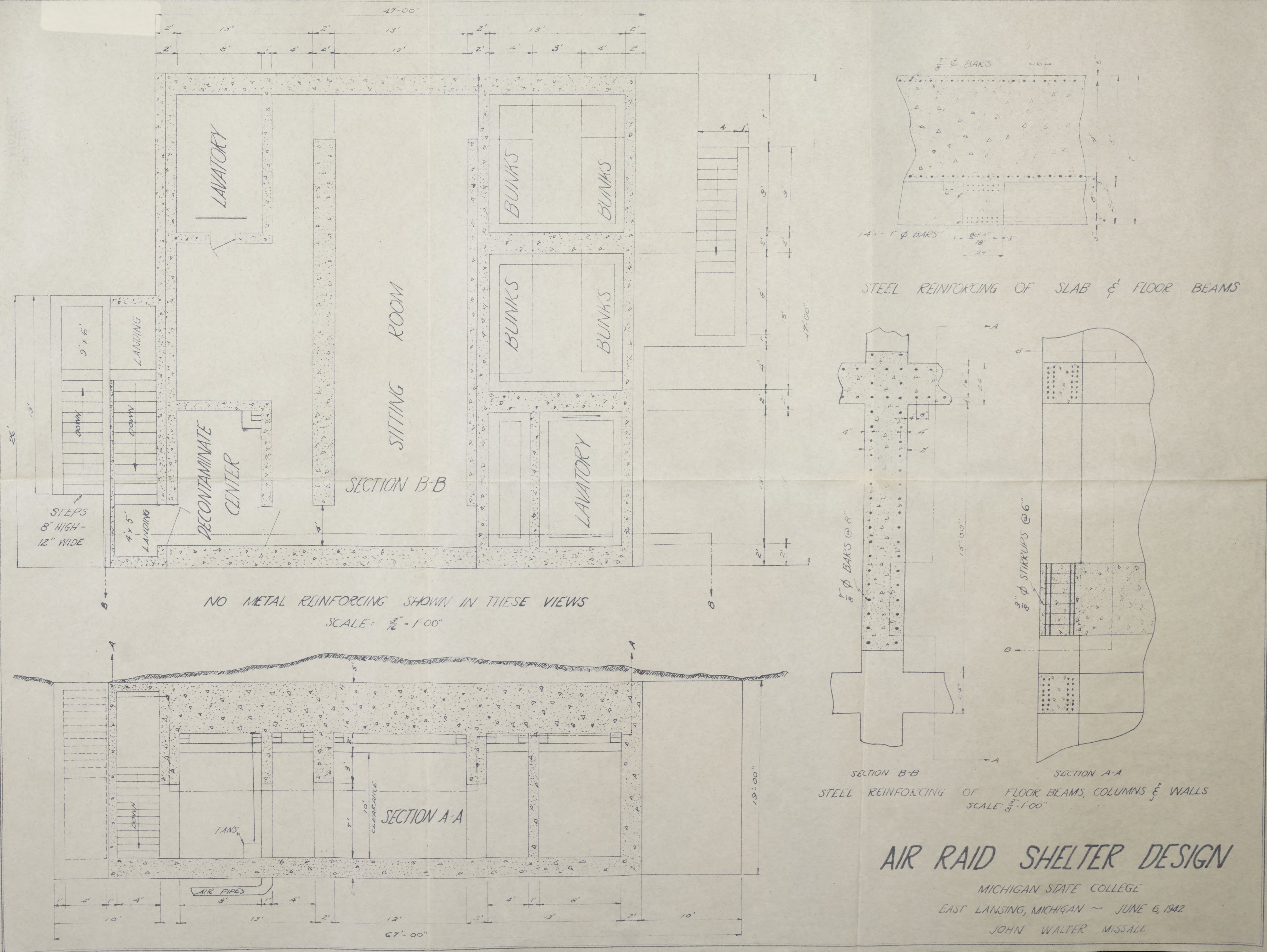
NOTES



AIR RAID SHELTER DESIGN

MICHIGAN STATE COLLEGE

EAST LANSING, MICHIGAN ~ JUNE 6, 1942

JOHN WALTER MISSALL