APPENDIX 2: BLAST, FRAGMENT, AND SHOCK LOADS

APPENDIX 2A ILLUSTRATIVE EXAMPLES

PROBLEM 2A-1 FREE-AIR BURST

Problem: **Determine incident blast wave parameters for a point of interest in the air for a free air burst.**

Procedure:

Step 1. Determine the charge weight and height of burst H_c. Select point of interest in the air relative to the charge.

Step 2. Apply a 20% safety factor to the charge weight.

Step 3. For the point of interest, calculate slant distance R and scaled slant distance Z:

$$Z = R/W^{1/3}$$

Step 4. Determine incident blast wave parameters from Figures 2-7 (+) and 2-8 (+) for the calculated value of the scaled slant distance Z.

From Figure 2-7 (+) read:

Peak positive incident pressure P_{so}

Shock front velocity U

Scaled unit positive incident impulse $i_s/W^{1/3}$

Scaled positive phase duration $t_o/W^{1/3}$

Scaled arrival time $t_A/W^{1/3}$

Scaled wave length of positive phase $L_w/W^{1/3}$

From Figure 2-8 (+) Read:

Peak negative incident pressure P_{so}^-

Scaled unit negative incident impulse $i_s^- / W^{1/3}$

Scaled negative phase duration $t_o^- / W^{1/3}$

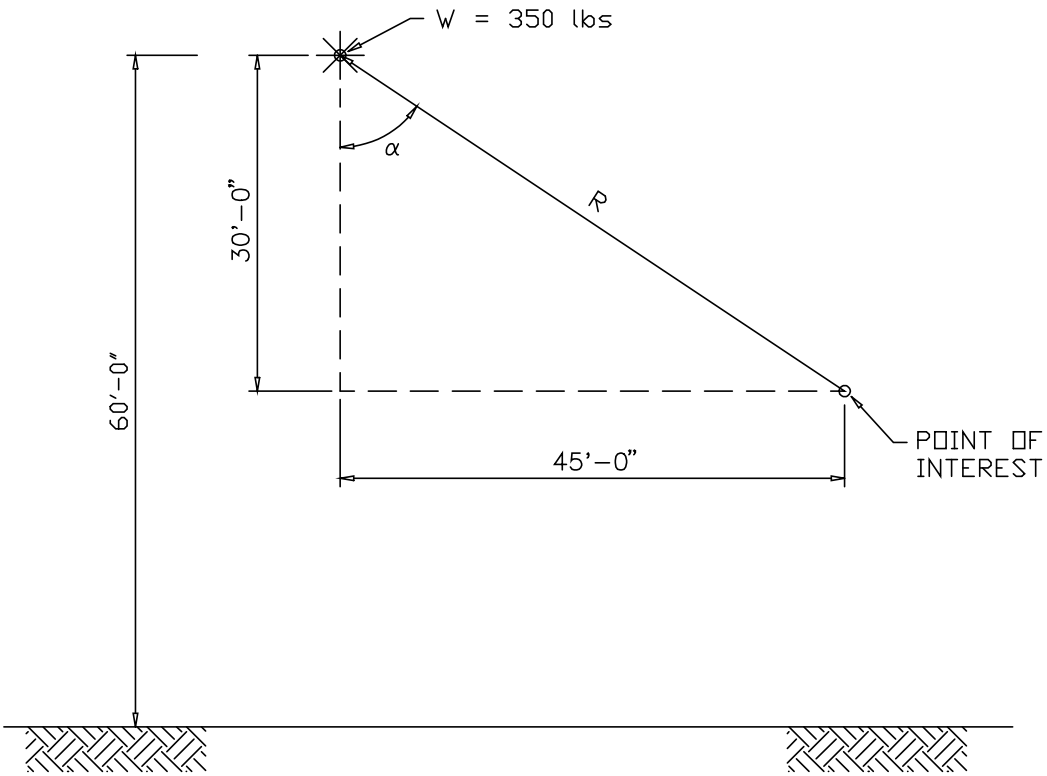
Scaled wave length of negative phase $L_w^- / W^{1/3}$

Multiply scaled values by $W^{1/3}$ to obtain absolute values.

EXAMPLE 2A-1 FREE-AIR BURST

Required: Incident blast wave parameters P_{so}, P_{so}^{-}, U, i_s, i_s^{-}, t_o, t_o^{-}, t_A, L_w^{-} at a point 30 ft below and 45 ft away in the air from an air burst of 290 lbs at a height of burst of 60 ft above the ground.

Figure 2A-1



Solution:

Step 1. Given: Charge weight = 290 lbs, H_c = 60 ft

Step 2. W = 1.2 (290) = 350 lbs

Step 3. For the point of interest:

$$R = \left[(45)^2 + (30)^2\right]^{1/2} = 54.1 \text{ ft}$$

$$Z = \frac{R}{W^{1/3}} = \frac{54.1}{(350)^{1/3}} = 7.67 \text{ ft/lb}^{1/3}$$

Step 4. Determine incident blast wave parameters for

Z = 7.67 ft/lb$^{1/3}$

From Figure 2-7 (+):

P_{so} = 11.2 psi

U = 1.34 ft/ms

$i_s / W^{1/3}$ = 7.0 psi-ms/lb$^{1/3}$, i_s = 7.0 (350)$^{1/3}$ = 49.3 psi-ms

$t_o / W^{1/3}$ = 2.05 ms/lb$^{1/3}$, t_o = 2.05 (350)$^{1/3}$ = 14.45 ms

$t_A / W^{1/3}$ = 3.15 ms/lb$^{1/3}$, t_A = 3.15 (350)$^{1/3}$ = 22.2 ms

$L_w / W^{1/3}$ = 2.0 ft/lb$^{1/3}$, L_w = 14.09 ft

From Figure 2-8 (+):

P_{so} = 1.63 psi

$i_s^- / W^{1/3} = 7.2 \text{ psi-ms/lb}^{1/3}, i_s^- = 7.2(350)^{1/3} = 50.74 \text{ psi-ms}$

$t_o^- / W^{1/3} = 8.4 \text{ ms/lb}^{1/3}, t_o^- = 8.4(350)^{1/3} = 59.20 \text{ ms}$

$L_w^- / W^{1/3} = 5.8 \text{ ft/lb}^{1/3}, L_w^- = 5.8(350)^{1/3} = 40.87 \text{ ft}$

PROBLEM 2A-2 AIR BURST

Problem: **Determine free-field blast wave parameters at a point on the ground for an air burst.**

Procedure:

Step 1. Select point of interest on the ground relative to the charge. Determine the charge weight, height of burst H_c, and ground distance R_G.

Step 2. Apply a 20% safety factor to the charge weight.

Step 3. Calculate scaled height of burst and angle of incidence α:

$$H_c / W^{1/3}$$

$$\alpha = \tan^{-1} (R_G/H_c)$$

Step 4. Determine peak reflected pressure $P_{r\alpha}$ and scaled unit positive reflected impulse $i_{r\alpha}/W^{1/3}$ in Mach front from Figures 2-9 (+) and 2-10 (+), respectively, for corresponding scaled height of burst and angle of incidence α:

Read $P_{r\alpha}$ and $i_{r\alpha}/W^{1/3}$

Multiply scaled value by $W^{1/3}$ to obtain absolute value.

Step 5. Read scaled distance Z from Figure 2-7 (+) for corresponding peak incident pressure $P_{so} = P_{r\alpha}$ in the Mach front.

Step 6. Determine shock front velocity U and scaled time of arrival of blast wave $t_A/W^{1/3}$ from Figure 2-7 (+) for value Z from Step 5. Multiply scaled value of $W^{1/3}$ to obtain absolute value.

Step 7. Read scaled distance Z from Figure 2-7 (+) for corresponding scaled unit positive incident impulse $i_s/W^{1/3} = i_{r\alpha}/W^{1/3}$ in the Mach front.

Step 8. Determine scaled positive duration of positive phase from Figure 2-7 (+) for the value of Z from Step 7. Multiply scaled value of $W^{1/3}$ to obtain absolute value.

EXAMPLE 2A-2 AIR BURST

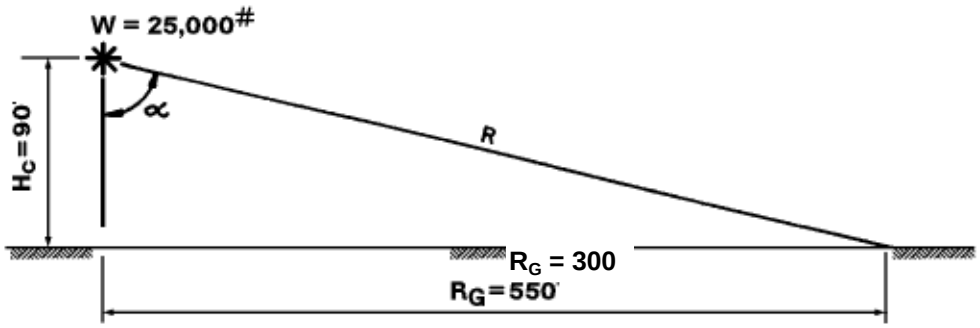
Required: Free-field blast wave parameters P_{so}, U, i_s, t_o, t_A for an air burst of 20,800 lbs at a ground distance of 300 ft and a height of burst of 90 ft.

Solution:

Step 1. Given: Charge weight = 20,800 lb, R_G = 300 ft, H_c = 90 ft

Step 2. W = 1.20 (20,800) = 25,000 lbs

Figure 2A-2



Step 3. For point of interest

$$H_c/W^{1/3} = 90/(25{,}000)1/3 = 3.08 \text{ ft/lb}^{1/3}$$

$$\alpha = \tan^{-1}\left[\frac{R_G}{H_c}\right] = \tan^{-1}[300/90] = 73.3°$$

Step 4. Determine reflected pressure $P_{r\alpha}$ and reflected impulse in the Mach front from Figure 2-9 (+) and 2-10 (+).

$$H_c/W^{1/3} = 3.08 \text{ ft/lb}^{1/3} \text{ and } \alpha = 73.3°$$

$$P_{r\alpha} = 10.1 \text{ psi}$$

$$\frac{i_{r\alpha}}{W^{1/3}} = 9.2 \text{ psi-ms/lb}^{1/3}, i_{r\alpha} = 9.2(25{,}000)^{1/3} = 269.0 \text{ psi-ms}$$

Step 5. Read scaled distance Z from Figure 2-7 (+) corresponding to $P_{so} = P_{r\alpha}$ = 10.1 psi

$$Z = 7.8 \text{ ft/lb}^{1/3}$$

Step 6. Determine U and $t_A/W^{1/3}$ from Figure 2-7 (+) corresponding to Z = 7.8 ft/lb$^{1/3}$.

U = 1.38 ft/ms

$t_A/W^{1/3}$ = 3.23 ms/lb$^{1/3}$, t_A = 3.23 (25,000)1/3 = 94.4 ms

Step 7. Read scaled distance *Z* from Figure 2-7 (+) corresponding to

$i_s/W^{1/3} = i_{r\alpha}/W^{1/3}$ = 9.2 psi-ms/lb$^{1/3}$

Z = 5.7 ft/lb$^{1/3}$

Step 8. Determine $t_o/W^{1/3}$ from Figure 2-7 (+) corresponding to

Z = 5.7 ft/lb$^{1/3}$

$t_o/W^{1/3}$ = 1.63 ms/lb$^{1/3}$, t_o = 1.63(25,000)$^{1/3}$ = 47.7 ms

PROBLEM 2A-3 SURFACE BURST

Problem: **Determine free-field blast wave parameters for a surface burst.**

Procedure:

Step 1. Select point of interest on the ground relative to the charge. Determine the charge weight, and ground distance R_G.

Step 2. Apply a 20% safety factor to the charge weight.

Step 3. Calculate scaled ground distance Z_G:

$$Z_G = \frac{R_G}{W^{1/3}}$$

Step 4. Determine free-field blast wave parameters from Figure 2-15 (+) for corresponding scaled ground distance Z_G:

Read:

Peak positive incident pressure P_{so}

Shock front velocity U

Scaled unit positive incident impulse $i_s/W^{1/3}$

Scaled positive phrase duration $t_o/W^{1/3}$

Scaled arrival time $t_A/W^{1/3}$

Multiply scaled values by $W^{1/3}$ to obtain absolute values.

EXAMPLE 2A-3 SURFACE BURST

Required: Free-field blast wave parameters P_{so}, U, i_s, t_o, t_A for a surface burst of 20,800 lbs at a distance of 530 ft

Solution:

Step 1: Given: Charge weight = 20,800 lb, R_G = 530 ft

Step 2. W = 1.20 (20,800) = 25,000 lbs

Step 3. For point of interest:

$$Z_G = \frac{R_G}{W^{1/3}} = \frac{530}{(25{,}000)^{1/3}} = 18.1 \text{ft/lb}^{1/3}$$

Step 4. Determine blast wave parameters from Figure 2-15 (+) for

Z_G = 18.1 ft/lb$^{1/3}$

P_{so} = 3.45 psi

U = 1.22 ft/ms

$$\frac{i_s}{W^{1/3}} = 4.7 \text{ psi} \cdot \text{ms/lb}^{1/3}, i_s = 4.7\,(25{,}000)^{1/3} = 137.4 \text{ psi - ms}$$

$$\frac{t_o}{W^{1/3}} = 3.3 \text{ ms/lb}^{1/3}, t_o = 3.3\,(25{,}000)^{1/3} = 96.5 \text{ ms}$$

$$\frac{t_A}{W^{1/3}} = 10.6 \text{ ms/lb}^{1/3}, t_A = 10.6\,(25{,}000)^{1/3} = 310 \text{ ms}$$

PROBLEM 2A-4 SHOCK LOADS ON CUBICLE WALLS

Problem: **Determine the average peak reflected pressure and average scaled reflected impulse acting on the wall of a cubicle from an internal explosion. The cubicle is fully vented.**

Procedure:

Step 1. Select from Figure 2-51 (+) the structural configuration which will define the number N and location of effective reflecting surfaces for the wall of the structure in question. Determine the charge weight, and, as defined by the structural configuration chosen above, the charge location parameters R_A, h, l and the structural parameters L, H.

Step 2. Apply a 20% safety factor to the charge weight.

Step 3. Calculate the chart parameters h/H, l/L, L/R_A, and the scaled distance Z_A.

Note: Use of the average pressure and impulse charts may require interpolation in many cases. Interpolation may be achieved by inspection for the scaled distance Z_A and by a graphical procedure for the chart parameters L/H, l/L, and h/H using 2 cycle x 2 cycle logarithmic graph paper. The following procedure will illustrate the interpolation of all three chart parameters.

Step 4. From Table 2-3 (+) determine the appropriate pressure and impulse charts for the number of adjacent reflecting surfaces N. Determine and tabulate the values of the average pressure P_r and average scaled impulse $i_r/W^{1/3}$ from these charts for the required L/R_A and Z_A and the following variables:

L/H = 0.625, 1.25, 2.50, and 5.00

l/L = 0.10, 0.25, 0.50, and 0.75

h/H = 0.10, 0.25, 0.50, and 0.75

Step 5. a. Prepare four 2-cycle log-log charts with L/H as the upperabscissa, l/L as the lowerabscissa, and P_r as the ordinate (one chart for each of the h/H ratios). On each chart for constant h/H and Z_A, plot i_b^- versus L/H for all l/L values.

Repeat with the ordinate labeled as $i_r/W^{1/3}$.

b. Using chart for h/H = 0.10, read values of P_r and $i_r/W^{1/3}$ versus l/L for required L/H. Tabulate results.

c. Repeat Step 5b for charts h/H = 0.25, 0.50, and 0.75. Tabulate results.

d. On each h/H chart, plot P_r and $i_r/W^{1/3}$ versus l/L from Steps 5b and 5c.

e. On each h/H chart, read P_r and $i_r/W^{1/3}$ for required l/L ratio.

f. On a fifth chart, plot P_r and $i_r/W^{1/3}$ from Step 5e versus h/H.

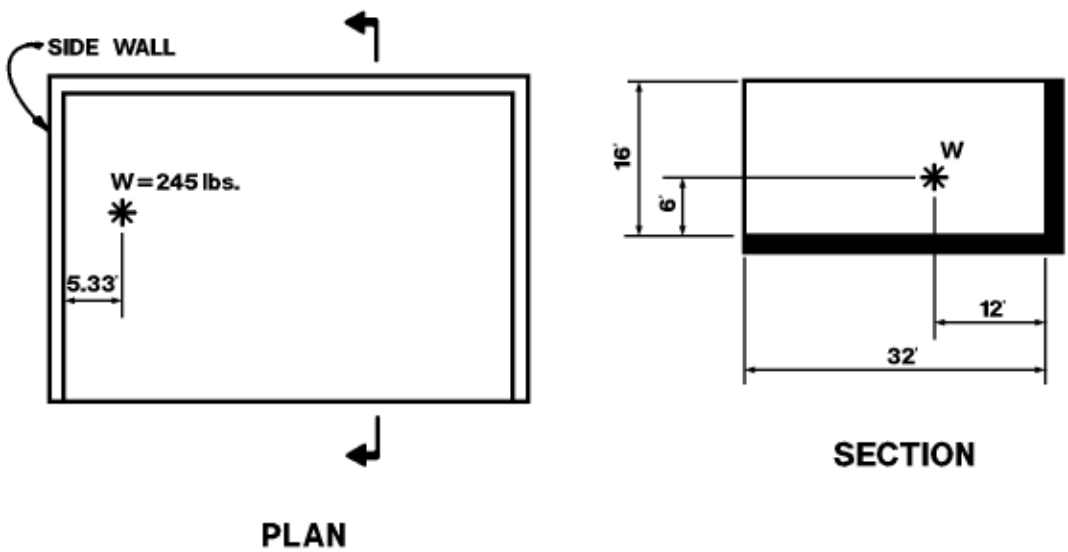
Step 6. For required h/H ratio, read P_r and $i_r/W^{1/3}$ from chart of Step 5f.

Step 7. Calculate duration of load on element from Equation 2-2.

EXAMPLE 2A-4 (A) SHOCK LOADS ON CUBICLE WALLS

Required: Average peak reflected pressure and average scaled reflected impulse on the side wall of a three-wall cubicle from an explosive charge of 205 lbs. The cubicle is fully vented.

Figure 2A-3



Solution:

Step 1. H = 16 ft L = 32 ft Charge Weight = 205 lbs

h = 6 ft l = 12 ft R_A = 5.33 ft

Note: For definition of terms, see Figure 2-51 (+) (side wall of three wall cubicle, N = 2).

Step 2. W = 1.20 (205) = 245 lbs

Step 3. h/H = 0.375 l/L = 0.375 L/R_A = 6.00 L/H = 2.00

$$Z_A = \frac{R_A}{W^{1/3}} = \frac{5.33}{(245)^{1/3}} = 0.85 \text{ ft/lb}^{1/3}$$

Interpolation is required for Z_A, L/H, l/L, and h/H.

Step 4. Determine and tabulate the values of P_r and $i_r/W^{1/3}$ from pressure and impulse charts (see Table 2-3 (+) for N = 2) for:

L/R_A = 6.00, Z_A = 0.85

(interpolate by inspection) and for values given for *L*/*H*, *l*/*L* and *h*/*H*. The results are tabulated in Table 2A-1 (+/+) and Table 2A-2 (+/+).

Step 5.

a. Use the information in Table 2A-1 (+/+) and Table 2A-2 (+/+) to plot P_r and $i_r/W^{1/3}$ versus *L*/*H* for the values of *l*/*L* and constant *h*/*H* (Figure 2A-4 (+/+/+/+) and Figure 2A-5 (+/+/+/+)). These are plotted as lines on Figure 2A-4 and Figure 2A-5 where L/H is on the upper abscissa and each line represents a column in Table 2A-1 and Table 2A-2 with a constant value of l/L.

b. Determine P_r and $i_r/W^{1/3}$ at*L*/*H* = 2.00 for each of the four l/L ratios from the appropriate line in Figure 2A-4a (+) and Figure 2A-5a (+). These are plotted as points on Figure 2A-4 and Figure 2A-5, where each point represents P_r or $i_r/W^{1/3}$ for L/H =2.00, *h*/*H* = 0.10 and given values of l/L on the lower abscissa.

c. Repeat above step for *h*/*H* = 0.25, 0.50, and 0.75 by entering Figure 2A-4b through d (+/+/+) and Figure 2A-5b through d (+/+/+) with *L*/*H* = 2.00 (tabulation of results not shown).

d. On each *h*/*H* chart, plot P_r and $i_r/W^{1/3}$ (Steps 5b and 5c) versus *l*/*L* (lowerabscissa of Figure 2A-4a through d (+/+/+/+) and Figure 2A-5a through d (+/+/+/+)).

e. Determine P_r and $i_r/W^{1/3}$ for *l*/*L* = 0.375 on each *h*/*H* chart of Figure 2A-4 and Figure 2A-5 with *l*/*L* = 0.375 and reading curves plotted in Step 5d. This is shown in Figure 2A-4 and Figure 2A-5 with a dashed line.

f. Plot P_r and $i_r/W^{1/3}$ (Step 5e) versus *h*/*H* (Figure 2A-6 (+/+)).

Table 2A-1 Average Pressure, Part 1

h*/*H	**0.10**				**0.25**			
l*/*L	**0.10**	**0.25**	**0.50**	**0.75**	**0.10**	**0.25**	**0.50**	**0.75**
L/*H* 0.625	462	569	598	569	533	665	701	665
1.25	749	932	980	932	943	1178	1238	1178
2.50	1200	1488	1562	1488	1432	1796	1881	1796
5.00	2032	2519	2635	2519	1870	2334	2437	2334
Figure	2-64 (+/+/+/+)	2-65 (+/+/+/+)	2-66 (+/+/+/+)	2-67 (+/+/+/+)	2-68 (+/+/+/+)	2-69 (+/+/+/+)	2-70 (+/+/+/+)	2-71 (+/+/+/+)

Table 2A-1 Average Pressure, Part 2

h/H	**0.50**				**0.75**			
l/L	**0.10**	**0.25**	**0.50**	**0.75**	**0.10**	**0.25**	**0.50**	**0.75**
L/H 0.625	546	681	718	681	533	665	701	665
1.25	1017	1267	1333	1267	943	1178	1238	1178
2.50	1609	2028	2120	2028	1432	1796	1881	1796
5.00	1987	2456	2563	2456	2623	3119	3210	3119
Figure	2-72 (+/+/+/+)	2-73 (+/+/+/+)	2-74 (+/+/+/+)	2-75 (+/+/+/+)	2-76 (+/+/+/+)	2-77 (+/+/+/+)	2-78 (+/+/+/+)	2-79 (+/+/+/+)

Table 2A-2 Average Unit Impulses, Part 1

h/H	**0.10**				**0.25**			
l/L	**0.10**	**0.25**	**0.50**	**0.75**	**0.10**	**0.25**	**0.50**	**0.75**
L/H 0.625	73	71	70	66	65	61	59	55
1.25	96	92	90	84	96	92	90	83
2.50	126	121	121	111	139	131	129	120
5.00	172	164	164	153	167	153	154	143
Figure	2-113 (+/+/+/+)	2-114 (+/+/+/+)	2-115 (+/+/+/+)	2-116 (+/+/+/+)	2-117 (+/+/+/+)	2-118 (+/+/+/+)	2-119 (+/+/+/+)	2-120 (+/+/+/+)

Table 2A-2 Average Unit Impulses, Part 2

h/H	**0.50**				**0.75**			
l/L	**0.10**	**0.25**	**0.50**	**0.75**	**0.10**	**0.25**	**0.50**	**0.75**
L/H 0.625	64	61	58	54	59	56	53	49
1.25	93	87	83	76	87	79	76	70
2.50	129	120	118	109	117	106	103	95
5.00	186	168	168	158	201	189	189	179
Figure	2-121 (+/+/+/+)	2-122 (+/+/+/+)	2-123 (+/+/+/+)	2-124 (+/+/+/+)	2-125 (+/+/+/+)	2-126 (+/+/+/+)	2-127 (+/+/+/+)	2-128 (+/+/+/+)

Figure 2A-4 Z_A=0.8523

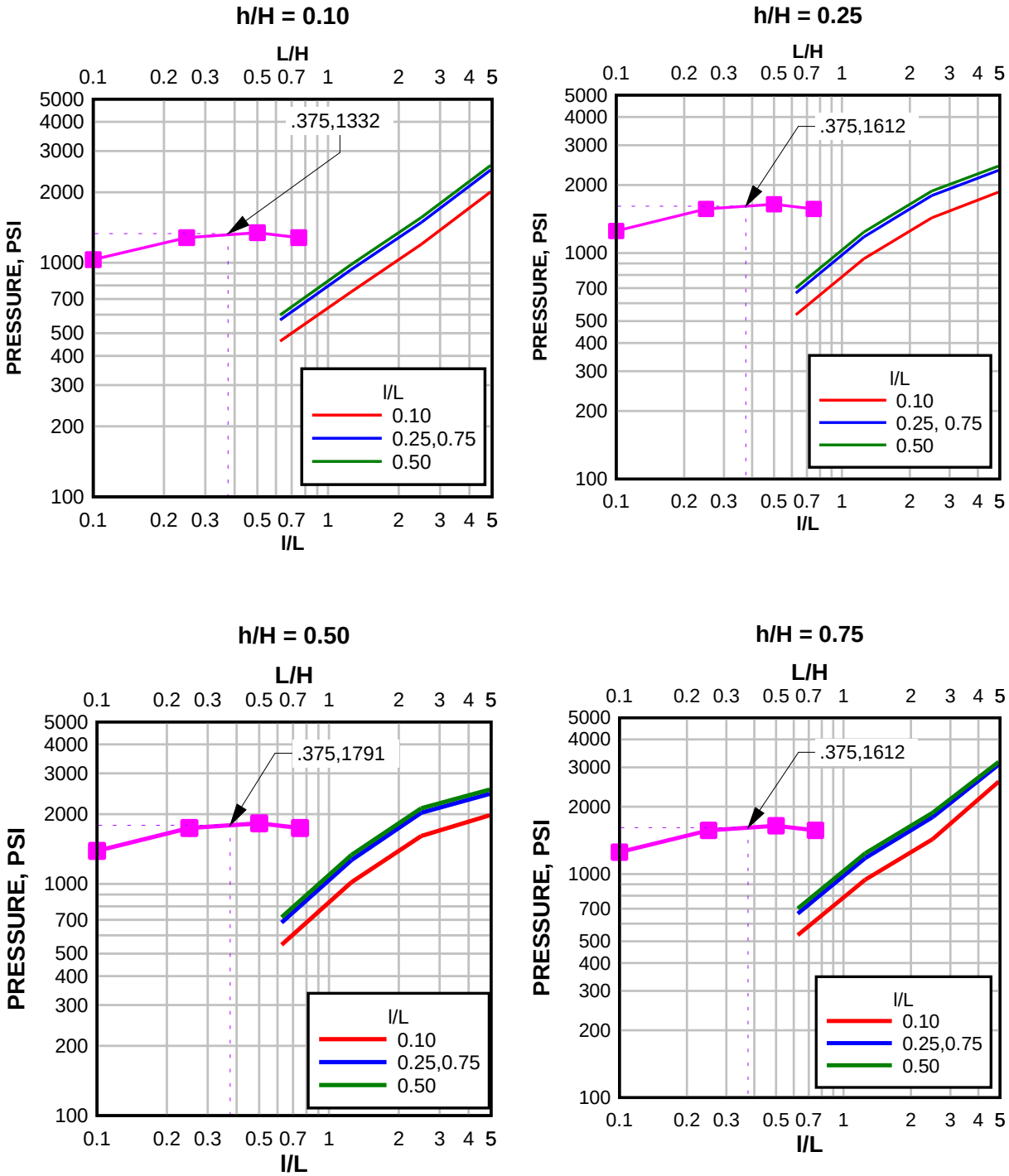
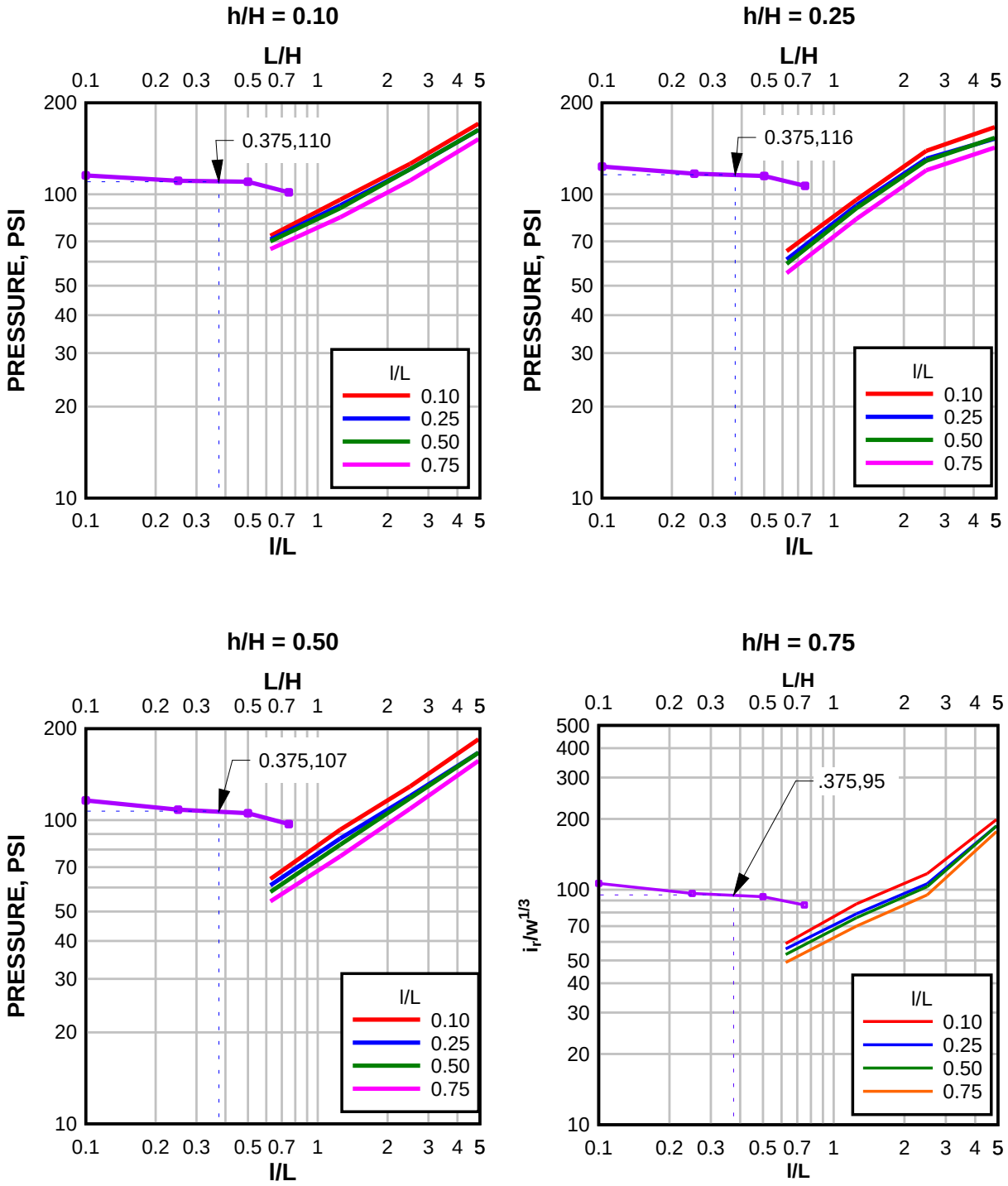


Figure 2A-5 Z_A=0.8523



h/H	P_r	$i_r/W^{1/3}$
0.10	1332	110
0.25	1612	116
0.50	1791	107
0.75	1612	95

Step 6. For h/H = 0.375 read P_r = 1714 psi on Figure 2A-6 (+/+) and read $i_r/W^{1/3}$ = 111 psi-ms/lb$^{1/3}$ on Figure 2A-6

Step 7. Calculate duration of load on wall.

$t_o = 2(i_r/W^{1/3})\ (W)^{1/3} / P_r = 2\ (111)\ (245)^{1/3} / 1714 = 0.81$ ms

Figure 2A-6a

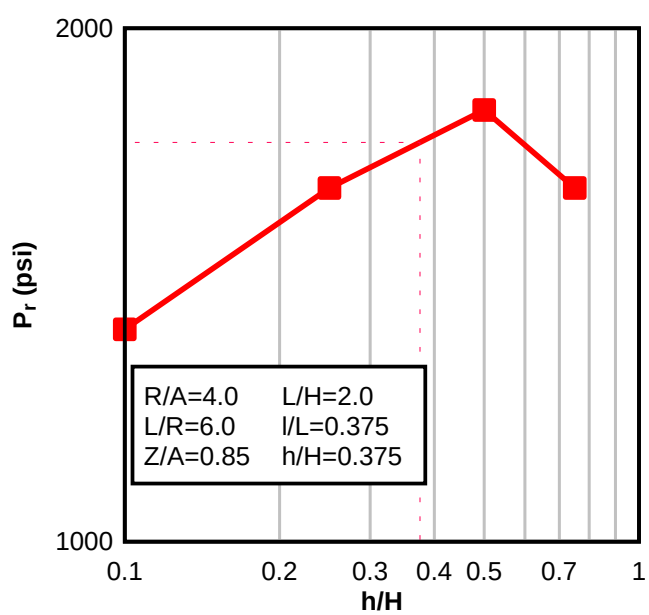
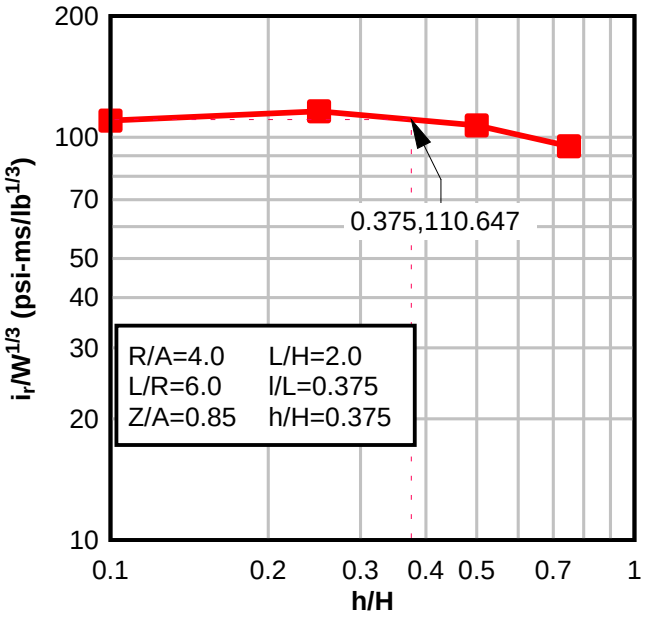


Figure 2A-6b


200
100
70
50
40
30
20
10
0.1
0.2
0.3
0.4
0.5
0.7
1
h/H
$i_r/W^{1/3}$ (psi-ms/lb$^{1/3}$)
0.375,110.647
R/A=4.0
L/H=2.0
L/R=6.0
l/L=0.375
Z/A=0.85
h/H=0.375

EXAMPLE 2A-4 (B) SHOCK LOADS ON CUBICLE WALLS

Required: Average peak reflected pressure and average scaled reflected impulse on the back wall of a three-wall cubicle from an explosive charge of 3,750 lbs. The cubicle is fully vented and shown in Figure 2A-7 (+).

Solution:

Step 1. H = 16 ft L = 36 ft Charge weight = 3,750 lbs

h = 4 ft l = 9 ft R_A = 16.5 ft

Note: For definition of terms, see Figure 2-51 (+) (back wall of three-wall cubicle, N = 3).

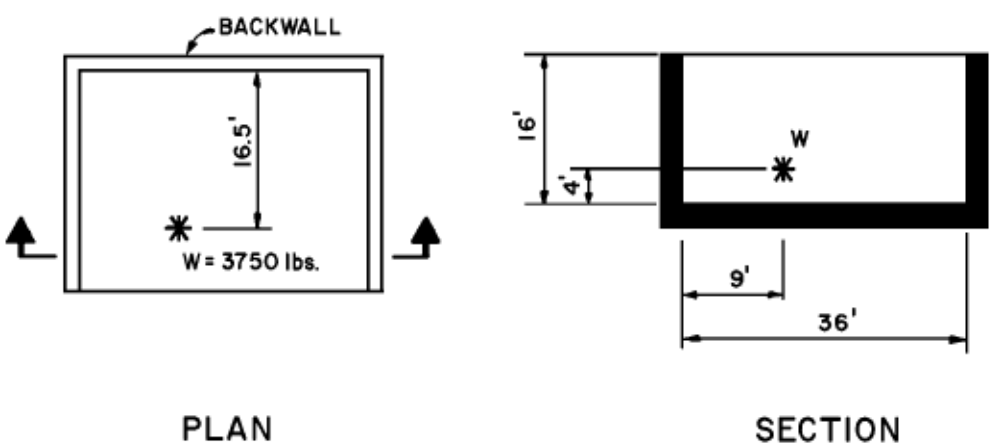
Step 2. W = 1.20 (3,750) = 4,500 lbs

Step 3. h/H = 0.25 l/L = 0.25 L/R_A = 2.18 L/H = 2.25

$$Z_A = \frac{R_A}{W^{1/3}} = \frac{16.5}{(4{,}500)^{1/3}} = 1.00\ ft\ /\ lb^{1/3}$$

Interpolation is required for L/H

Figure 2A-7



Step 4. Determine the values of P_r and $i_r/W^{1/3}$ from Figures 2-84 (+/+/+/+) and 2-133 (+/+/+/+) (determined from Table 2-3 (+) for N = 3, h/H = 0.25, l/L = 0.25) for L/H ratios of 0.625, 1.25, 2.50 and 5.00.

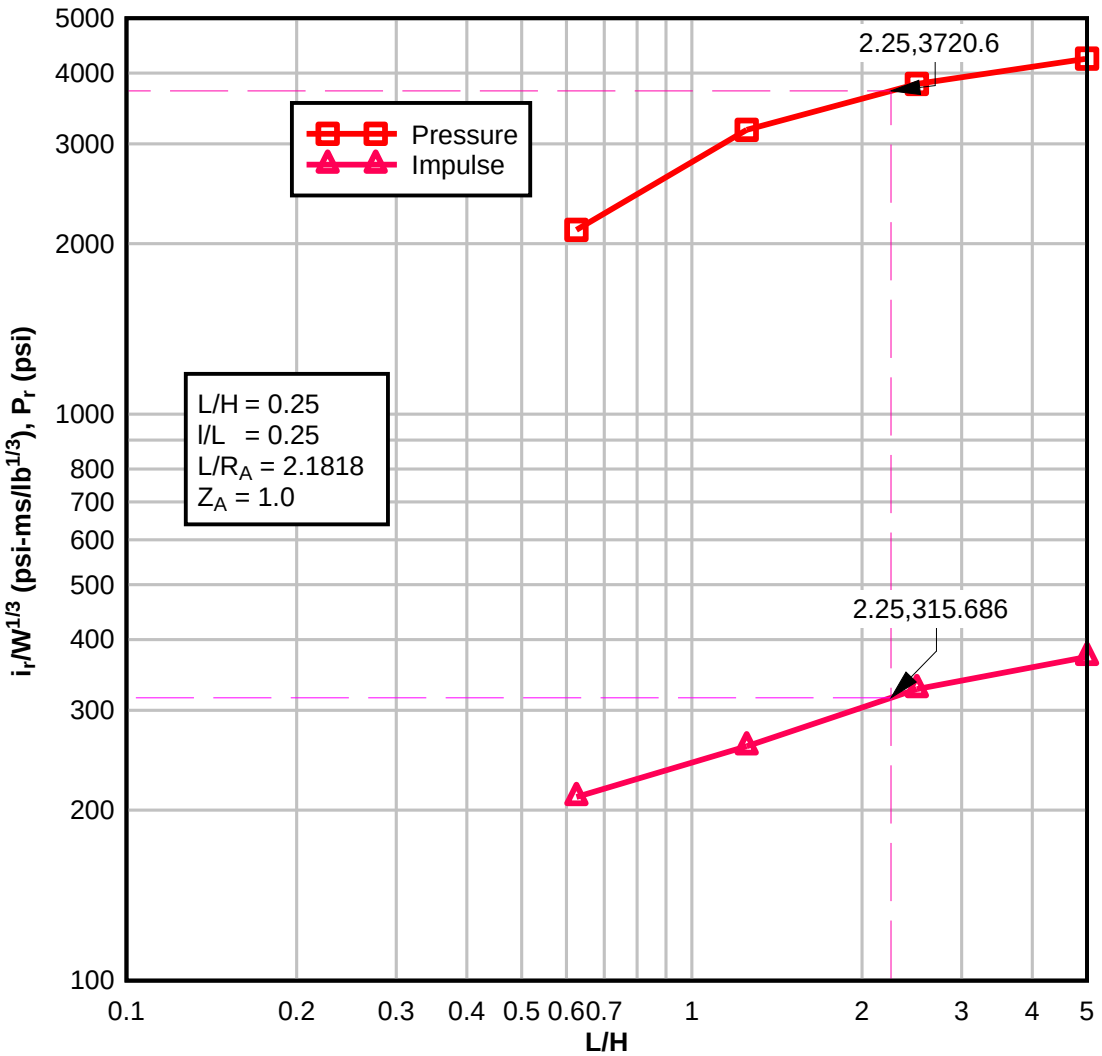
Step 5. Plot P_r and $i_r/W^{1/3}$ versus L/H (Figure 2A-8 (+)).

Step 6. For L/H = 2.25 read, P_r = 3700 psi and $i_r/W^{1/3}$ = 295 psi- ms/lb$^{1/3}$ and on Figure 2A-8 (+).

Step 7. Calculate duration of load on wall (Equation 2-2).

$$t_o = 2(i_r/W^{1/3})\ W^{1/3}/P_r\ = 2\ (295)\ (4500)^{1/3}/3700 = 2.63 \text{ ms}$$

Figure 2A-8



PROBLEM 2A-5 EFFECT OF FRANGIBILITY ON SHOCK LOADS

Problem: **Determine average peak reflected pressure and average reflected impulse acting on the wall of a cubicle due to an internal explosion. One of the reflection surfaces is a frangible wall.**

Procedure:

Step 1. Determine the average peak reflected pressure P_r and the average reflected impulse acting on the element in question according to the procedure in Problem 2A-4 assuming that the adjoining frangible element will remain in place and provide full reflection.

Step 2. Determine the average reflected impulse acting on the element in question according to the procedure in Problem A-4 assuming that the adjoining frangible element is not in place.

Step 3. Subtract the average impulse determined in Step 2 from the one in Step 1.

Step 4. Calculate unit weight of the frangible element W_F and divide by the sixth root of the charge weight (apply a 20% factor of safety to the charge weight).

Step 5. Calculate the normal scaled distance Z between the center of the charge and the surface of the frangible element.

Step 6. Determine the reflection factor f_r from Figure 2-150 (+) for the values of $W_F/W^{1/6}$ from Step 4 and Z from Step 5. Interpolate for value of Z if required.

Step 7. Determine the magnitude of the impulse load reflected from the frangible element to the element in question by multiplying the value of the average impulse from Step 3 and f_r from Step 6.

Step 8.
a. Determine the total impulse load acting on the element in question by adding the impulse values from Steps 2 and 7.

b. The peak average reflected pressure of the shock load is equal to the value of P_r in Step 1.

c. Determine the duration of the load from Equation 2-2.

EXAMPLE 2A-5 EFFECT OF FRANGIBILITY ON SHOCK LOADS

Required: Average peak reflected pressure and average reflected impulse on the back wall of the cubicle described in Example 2A-4(B) except the left side wall is a 10 psf frangible element. The charge weight is 3,750 lbs (see Figure 2A-7 (+)).

Solution:

Step 1. Assuming the frangible side wall provides full reflection of the blast wave, P_r and i_r for the back wall according to the procedure in Problem 2A-4 are:

P_r = 3700.0 psi

i_r = 4870.3 psi-ms

Step 2. Assuming no left side wall, the average reflected impulse on the back wall, according to procedure in Problem 2A-4 is:

i_r = 3962.3 psi-ms

Step 3. Calculate the reflected impulse contributed by the left side wall by subtracting the impulse value of Step 2 from Step 1.

δi_r = 4870.3 - 3962.3 = 908.0 psi-ms

Step 4. a. W_F = 10 lb/ft^2 (given)

b. W = 3,750 x 1.20 = 4,500 lbs

c. Calculate $W_F/W^{1/6}$ ratio:

$W_F/W^{1/6} = 10/(4500)^{1/6} = 2.46$

Step 5. a. R = 9.0 feet (see Figure 2A-7 (+))

b. Calculate normal scale distance Z:

$$Z = \frac{R}{W^{1/3}} = \frac{9}{(4500)^{1/3}} = 0.545 \text{ ft/lb}^{1/3}$$

Step 6. From Figure 2-150 (+) where $W_F/W^{1/6}$ = 2.46 and Z = 0.545 read: f_r = 0.68

Step 7. Determine the magnitude of the impulse reflected from the frangible left side wall, using f_r = 0.68 and the impulse from Step 3.

i_r (left side wall) = 908 (0.68) = 617.4 psi-ms

Step 8. a. Calculate total reflected impulse on the back wall by adding impulse values from Steps 2 and 7.

i_r (back wall) = 3962.3 + 617.4 = 4579.7 psi-ms

b. Peak reflected pressure from Step 1:

P_r = 3700 psi

c. Calculate duration of load on wall:

$$t_o = \frac{2i_r}{P_r} = \frac{2(4579.7)}{3700} = 2.48\text{ms}$$

PROBLEM 2A-6 SHOCK LOADS ON FRANGIBLE ELEMENTS

Problem: **Determine the average peak reflected pressure and average reflected impulse acting on the frangible wall of a cubicle due to an internal explosion.**

Procedure:

Step 1. Determine the average peak reflected pressure P_r and the average reflected impulse acting on the element in question according to the procedure in Problem 2A-4, assuming that the wall will remain intact.

Step 2. Calculate the unit weight of the frangible element W_F and divide by the sixth root of the charge weight (apply a 20% factor of safety to the charge weight).

Step 3. From Figure 2-7 (+) determine the fictitious scaled distance Z which corresponds to the average scaled impulse determined in Step 1.

Step 4. Using the value of $W_F/W^{1/6}$ from Step 2 and the Z from Step 3, determine the reflection factor f_r from Figure 2-150 (+). Interpolate for value of Z if required.

Step 5.
a. Calculate the value of the average impulse contributing to the translation of the frangible element by multiplying the values of i_r and f_r of Steps 1 and 4 respectively.

b. The peak average reflected pressure of the shock load is equal to the value of P_r in Step 1.

c. Determine the duration of the load from Equation 2-2.

EXAMPLE 2A-6 SHOCK LOADS ON FRANGIBLE ELEMENTS

Required: Average peak reflected pressure and average scaled reflected impulse on the back wall of the cubicle described in Example 2A-4 except the back wall is a 10 psf frangible wall. The charge weight is 3,750 lbs (see Figure 2A-7 (+)).

Solution:

Step 1. P_r and i_r for the back wall, assuming it is a rigid element, according to procedure in Problem 2A-4 are:

P_r = 3700.0 psi

$i_r/W^{1/3}$ = 295.0 psi-ms/lb$^{1/3}$

i_r = 4870.3 psi-ms

Step 2. a. W_F = 10.0 lb/ft^2 (given)

b. W = 3.750 x 1.20 = 4,500 lbs

c. Calculate $W_F/W^{1/6}$ ratio:

$W_F/W^{1/6}$ = 10/(4500)$^{1/6}$ = 2.46

Step 3. Read the fictitious scaled-distance Z corresponding to $i_r/W^{1/3}$ = 295 from Figure 2-7 (+).

Z = 0.82 ft/lb$^{1/3}$

Step 4. From Figure 2-150 (+) where $W_F/W^{1/6}$ = 2.46 and Z = 0.82 read:

f_r = 0.74

Step 5. a. Calculate reflected impulse on the frangible back wall by multiplying the value of impulse from Step 1 and f_r = 0.74

i_r (frangible back wall) - 4870.3 (0.74) = 3604.0 psi-ms

b. Peak reflected pressure from Step 1.

P_r = 3700 psi

c. Calculate duration of load on wall.

$$t_o = \frac{2i_r}{P_r} = \frac{2(3604.0)}{3700} = 1.95\text{ms}$$

PROBLEM 2A-7 GAS PRESSURE

Problem: **Determine the gas pressure-time loading inside a cubicle, with a small vent opening, due to an internal explosion. The vent opening may be sealed or unsealed with a frangible panel or cover.**

Procedure:

Step 1. Apply a 20% factor of safety to the charge weight.

Step 2. Calculate the free volume inside the cubicle V_f.

Step 3. Determine the charge weight to free volume ratio W/V_f.

Step 4. Determine the peak gas pressure P_g from Figure 2-152 (+) using the value of W/V_f from Step 3.

Step 5. Determine vent area A.

Step 6. Determine scaled value of the vent area $A/V^{2/3}$.

Step 7. a. Calculate the unit weight of the frangible panel W_F, if any.

b. Calculate the scaled unit weight of the frangible panel or cover $W_F/W^{1/3}$. Use $W_F/W^{1/3} = 0$ for no cover.

Step 8. Determine the scaled average reflected impulse on the element containing the vent opening with no cover according to the procedure outlined in Problem 2A-4 or on the frangible panel (cover) using the procedure of Problem 2A-6.

Step 9. Determine the scaled gas impulse from Figures 2-153 (+) to 2-164 (+). Use the values of W/V_f from Step 3, $W_F/W^{1/3}$ from Step 7, $A/V^{2/3}$ from Step 6 and $i_r/W^{1/3}$ from Step 8. Interpolate for values of W/V_f and $i_r/W^{1/3}$ if required. Multiply by $W^{1/3}$ to calculate gas impulse.

Step 10. Calculate the fictitious gas duration using Equation 2-4 and values of P_g and i_g from Steps 4 and 9, respectively.

EXAMPLE 2A-7 (A) GAS PRESSURE (SMALL VENT OPENING)

Required: **Gas pressure-time loading inside a 10' x 10' x 10' cubicle with a 2' x 2' vent opening on the rear wall. The charge weight is 833.3 pounds.**

Solution:

Step 1. Charge weight:

W = 833.3 x 1.20 = 1,000 lbs

Step 2. Free volume inside the structure:

V_f = 10' x 10' x 10' = 1,000 ft^3

Step 3. Charge weight to free volume ratio:

W/V_f = 1000.0/1000.0 = 1.0

Step 4. Read P_g from Figure 2-152 (+) for W/V_f = 1.0

P_g = 2,650 psi

Step 5. Vent area of 2' x 2' opening:

A = 2' x 2' = 4 ft^2

Step 6. Calculate scaled vent area:

$A/V^{2/3} = 4/1000^{2/3} = 0.04$ ft^2 /ft^2

Step 7. a. Vent has no cover.

b. Scaled weight of the cover:

$W_F/W^{1/3} = 0$

Step 8. Scaled average reflected impulse of the rear wall from procedure outlined in Problem 2A-4:

$i_r/W^{1/3}$ = 1225 psi-ms/lb$^{1/3}$

Step 9. Read scaled gas impulse from Figures 2-162 (+) to 2-164 (+) for $A/V^{2/3}$ = 0.04 and $W_F/W^{1/3}$ = 0.0. Interpolate for scaled impulse of

$i_r/W^{1/3}$ = 1225

$i_g/W^{1/3}$ = 7500 psi-ms/lb$^{1/3}$

i_g = 7,500 x 1,000$^{1/3}$ = 75,000.0 psi-ms

Step 10. Calculate fictitious duration of gas load from Equation 2-4.

$$t_g = \frac{2i_g}{P_g} = \frac{2 \times 75{,}000.0}{2{,}650} = 56.6 \text{ ms}$$

EXAMPLE 2A-7 (B) GAS PRESSURE (FRANGIBLE WALL)

Required: Gas pressure-time loading inside a 10' x 10' x 10' cubicle with a frangible wall of 10 psf as the rear wall. The charge weight is 833.3 pounds.

Solution:

Step 1. Charge weight:

W = 833.3 x 1.2 = 1,000 lbs

Step 2. Free volume inside the structure:

V_f = 10' x 10' x 10' = 1,000 ft^3

Step 3. Charge weight to free volume ratio:

W/V_f = 1000/1000 = 1.0

Step 4. Read P_g from Figure 2-152 (+) for W/V_f = 1.0.

P_g = 2650 psi

Step 5. Vent area of frangible wall:

A = 10' x 10' = 100 ft^2

Step 6. Calculate scaled vent area:

$A/V^{2/3} = 100/1000^{2/3} = 1.0$ ft^2/ft^2

Step 7. a. Unit density of the frangible wall: W_F = 10.0 lbs/ft^2 (given)

b. Scaled weight of the frangible wall: $W_F/W^{1/3} = 10/1000^{1/3} = 1.0$

Step 8. Scaled average reflected impulse of the rear frangible wall from procedure outlined in Problem 2A-6:

$i_r/W^{1/3}$ = 784 psi-ms/lb$^{1/3}$

Step 9. Read scaled gas impulse from Figures 2-162 (+) to 2-164 (+) for $A/V^{2/3}$ = 1.0 and $W_F/W^{1/3}$ = 1.0. Interpolate for scaled impulse of $i_r/W^{1/3}$ = 784.

$i_g/W^{1/3}$ = 400.0 psi-ms/lb$^{1/3}$

$i_g = 400.0 \times 1000^{1/3} = 4000$ psi-ms

Step 10. Calculate fictitious duration of gas load from Equation 2-4.

$$t_g = \frac{2i_g}{P_g} = \frac{2 \times 4000}{2650} = 3.02\,\text{ms}$$

PROBLEM 2A-8 LEAKAGE PRESSURES FROM FULLY VENTED THREE WALL CUBICLE

Problem: **Determine free-field blast wave parameters at a distance from a fully vented explosion inside a three wall cubicle.**

Procedure:

Step 1. Determine charge weight, distance in the desired direction and volume of structure.

Step 2. Apply a 20% safety factor to the charge weight.

Step 3. Calculate scaled distance and *W*/*V* ratio.

Step 4. Determine peak positive pressures using Figures 2-168 (+) or 2-169 (+).

Step 5. Determine maximum peak pressure for side and back directions from Figure 2-170 (+) using *W*/*V* ratio.

Step 6. For *W*/*V* ratio determine scaled positive impulses using Figures 2-171 (+) to 2-182 (+). Multiply by $W^{1/3}$ to calculate actual value of impulses.

Step 7. Determine shock parameters from Figure 2-15 (+) corresponding to the peak pressure from Step 4, except for the normal reflected impulse where the scaled impulse from Step 6 should be used.

EXAMPLE 2A-8 LEAKAGE PRESSURES FROM FULLY VENTED THREE WALL CUBICLE

Required: Blast wave parameters at a distance of 200 ft from an explosion located at the center of a three wall cubicle with no roof. The charge weight is 833.3 lbs and the interior dimensions of the cubicle are 17.5 ft x 17.5 ft x 13 ft high. Calculate the parameters at the front, side and back of the cubicle.

Solution:

Step 1. Given:

a. Charge weight = 833.3 lbs

b. R = 200 ft in all directions

c. V = 17.5 x 17.5 x 13 = 3980 ft^3

Step 2. Calculate W:

W = 1.20 x Charge Weight = 1.20 x 833.3 = 1000 lbs

Step 3. Calculate:

a. Scaled distance Z,

$$Z = \frac{R}{W^{1/3}} = \frac{200}{(1000)^{1/3}} = 20 \text{ ft/lbs}^{1/3}$$

b. W/V ratio,

W/V = 1000/3980 = 0.25 lbs/ft^3

Step 4. Determine peak incident pressure from Figure 2-168 (+):

P_{so} (front) = 5.5 psi

P_{so} (side) = 4.0 psi

P_{so} (back) = 2.8 psi

Step 5. For W/V = 0.25, read the maximum peak incident pressures from Figure 2-170 (+):

$(P_{so})_{max}$ (back and side) = 47.0 psi > 4.0 > 2.8

Step 6. Scaled positive impulse, for Z = 20 ft/lb$^{1/3}$ and W/V = 0.25 lbs/ft^3

$i_s/W^{1/3}$ (front) = 5.5 psi-ms/lb$^{1/3}$ Figure 2-171 (+)

i_s (front) = 5.5 x $1000^{1/3}$ = 55 psi-ms

$i_s/W^{1/3}$ (side) = 4.5 psi-ms/$lb^{1/3}$ Figure 2-173 (+)

i_s (side) = 4.5 x $1000^{1/3}$ = 45 psi-ms

$i_s/W^{1/3}$ (back) = 3.8 psi-ms/$lb^{1/3}$ Figure 2-175 (+)

i_s (back) = 3.8 x $1000^{1/3}$ = 38 psi-ms

Step 7. For peak positive pressures (P_{so}) read shock parameters from Figure 2-15 (+) at front, side and back directions.

a. For P_{so} (front) = 5.5 psi (Step 4)

U = 1.28 ft/ms

$t_o/W^{1/3}$ = 2.95 ms/$lb^{1/3}$

t_o = 2.95 x $1000^{1/3}$ = 29.5 ms

$t_A/W^{1/3}$ = 7.00 ms/$lb^{1/3}$

t_A = 7.00 x $1000^{1/3}$ = 70.0 ms

b. For P_{so} (side) = 4.0 psi (Step 4)

U = 1.24 ft/ms

$t_o/W^{1/3}$ = 3.20 ms/$lb^{1/3}$

t_o = 3.2 x $1000^{1/3}$ = 32.0 ms

$t_A/W^{1/3}$ = 9.30 ms/$lb^{1/3}$

t_A = 9.3 x $1000^{1/3}$ = 93.0 ms

c. For P_{so} (back) = 2.8 psi

U = 1.20 ft/ms

$t_o/W^{1/3}$ = 3.45 ms/$lb^{1/3}$

t_o = 3.45 x $1000^{1/3}$ = 34.5 ms

$t_A/W^{1/3}$ = 12.90 ms/$lb^{1/3}$

t_A = 12.9 x $1000^{1/3}$ = 129.0 ms

PROBLEM 2A-9 LEAKAGE PRESSURE FROM PARTIALLY VENTED FOUR WALL CUBICLE

Problem: **Determine free-field blast wave parameters at a distance from a partially vented explosion inside a four wall cubicle.**

Procedure:

Step 1. Determine charge weight, distance to point in question, vent area and volume of structure.

Step 2. Apply a 20% safety factor to the charge weight.

Step 3. Calculate distance Z, $A/V^{2/3}$ ratio and $AW^{1/3}/V$ ratio.

Step 4. Determine peak positive pressure using Figure 2-184 (+/+).

Step 5. Determine scaled positive impulses using Figure 2-185 (+). Multiply by $W^{1/3}$ to calculate actual value of impulses.

Step 6. Determine shock parameters from Figure 2-15 (+). Use the peak pressure from Step 4, except for normal reflected impulse where the scaled impulse(s) from Step 5 should be used.

EXAMPLE 2A-9 LEAKAGE PRESSURE FROM PARTIALLY VENTED FOUR WALL CUBICLE

Required: Blast wave parameters at distance of 200 ft from a charge located in an above ground four wall cubicle. The circular vent is located at the center of the roof and has a diameter of 4 ft The charge is 833.3 lbs and located at the center of 17.5' x 17.5' x 13' cubicle. Top of the roof is 15 feet above the ground level.

Solution:

Step 1. Given (see Figure 2-183b (+) for parameters):

a. Charge weight = 833.3 lbs

b. R = 200 ft, h = 15 ft

$$d_1 = \left[(4/2)^2 + (15 - 13/2)^2\right]^{1/2} = 8.73\ ft$$

d_2 = (17.5 - 4)/2 = 6.75 ft

$$d_3 = \left[(15)^2 + (200 - 4/2 - 6.75 - 15)^2\right]^{1/2} = 176.89\ ft$$

$R' = d_1 + d_2 + h + d_3$ =8.73 + 6.75 + 15 + 176.89 =207.37 ft

c. $A = \pi(2)^2 = 12.57\ ft^2$

d. V = 17.5 x 17.5 x 13 = 3,980 ft^3

Step 2. Calculate W:

W = 1.20 x charge weight = 1.20 x 833.3 = 1000 lbs

Step 3. Calculate:

a. Scaled distance Z.

$$Z = \frac{R'}{W^{1/3}} = \frac{207.37}{1000^{1/3}} = 20.7\ ft/lb^{1/3}$$

b. $A/V^{2/3} = 12.57/(3980)^{2/3} = 0.05$

c. $AW^{1/3}/V = 12.57\ (1000)^{1/3}\ /3{,}980 = 0.0316\ lb^{1/3}/ft$

Step 4. Peak positive pressure from Figure 2-184 (+/+) for Z = 20.7 and

$A/V^{2/3} = 0.050$

P_{so} = 0.95 psi

Step 5. Peak positive pressure impulse from Figure 2-185 (+) for Z = 20.7 and

$AW^{1/3}/V$ = 0.0316 $lb^{1/3}$/ft

$i_s/W^{1/3}$ = 1.80 psi-ms/$lb^{1/3}$

i_s = 1.8 x $1000^{1/3}$ = 18.0 psi-ms

Step 6. For peak positive pressure P_{so} = 0.95 psi, read shock parameters from Figure 2-15 (+).

U = 1.12 ft/ms

$t_o/W^{1/3}$ = 4.5 ms/$lb^{1/3}$

t_o = 4.5 x $1000^{1/3}$ = 45.0 ms

$t_A/W^{1/3}$ = 35.0 ms/$lb^{1/3}$

t_A = 35.0 x $1000^{1/3}$ = 350.0 ms

PROBLEM 2A-10 EXTERNAL BLAST LOADS ON STRUCTURES

Problem: **Determine the pressure-time blast loading curves on a rectangular structure from an external explosion.**

Procedure:

Step 1. Determine the charge weight, ground distance R_G, height of burst H_c (for air burst) and structure dimensions.

Step 2. Apply a 20% safety factor to the charge weight.

Step 3. Select several points on the structure (front wall, roof, rear wall, etc.) and determine free-field blast wave parameters for each point. For air burst, follow the procedure outlined in Problem 2A-2; a surface burst, Problem 2A-3; and leakage pressures, Problem 2A-8 or 2A-9.

Step 4. For the front wall:

a. Calculate peak positive reflected pressure $P_{r\alpha} = C_{r\alpha} \times P_{so}$. Read value of $C_{r\alpha}$ for P_{so} and α from Figure 2-193 (+).

b. Read scaled unit positive reflected impulse $i_{r\alpha}/W^{1/3}$ from Figure 2-194 (+/+) for P_{so} and α. Multiply scaled value by $W^{1/3}$ to obtain absolute value.

Note: If wave front is not plane, use average values.

Step 5. Determine positive phase of front wall loading.

a. Determine sound velocity in reflected overpressure region C_r from Figure 2-192 (+) for peak-incident pressure P_{so}.

b. Calculate clearing time t_c:

$$t_c = \frac{4S}{(1+R)C_r}(\text{ms}) \qquad \text{(Equation 2-3)}$$

where:

S = height of front wall or one-half its width, whichever is smaller.

G = maximum of wall height or one-half its width

$R = S/G$

c. Calculate fictitious positive phase duration t_{of}:

$$t_{of} = \frac{2i_s}{P_{so}} \qquad \text{(Equation 2-6)}$$

d. Determine peak dynamic pressure q_o from Figure 2-3 (+) for P_{so}.

e. Calculate $P_{so} + C_D q_o$. Obtain C_D from Section 2-15.3.2.

f. Calculate fictitious duration t_{rf} of the reflected pressure.

$$t_{rf} = \frac{2i_{r\alpha}}{P_{r\alpha}} \qquad \text{(Equation 2-11)}$$

g. Construct the positive pressure-time curve of the front wall similar to Figure 2-191 (+). The actual loading is the smaller of the impulse (area under curve) due to reflected pressure or cleared reflected pressure plus incident pressure.

Step 6. Determine negative phase of the front wall loading.

a. Read the values of Z from Figure 2-15 (+) for the value of $P_{r\alpha}$ from Step 4a and $i_{r\alpha}/W^{1/3}$ from Step 4b.

b. Determine $P_{r\alpha}^-$ and $i_{r\alpha}^-/W^{1/3}$ from Figure 2-16 (+) for the corresponding values of Z from Step 6a. Multiply scaled value of the negative impulse by $W^{1/3}$ to obtain absolute value.

c. Calculate the fictitious duration of the negative reflected pressure.

$$t_{rf}^- = 2i_{r\alpha}^-/P_{r\alpha} \qquad \text{(Equation 2-7)}$$

d. Calculate rise time of the negative pressure by multiplying t_{rf}^- by 0.25 (Section 2-15.3.2).

e. Construct the negative pressure-time curve similar to Figure 2-191 (+).

Step 7. Determine positive phase of side wall loading.

a. Calculate the wave length to span length ratio L_{wf}/L at front of the span.

b. Read values of C_E, $t_d/W^{1/3}$ and $t_{of}/W^{1/3}$ from Figures 2-196 (+), 2-197 (+) and 2-198 (+) respectively.

c. Calculate P_R, t_r and t_o.

d. Determine dynamic pressure q_o from Figure 2-3 (+) for P_R.

e. Calculate $P_R = C_E P_{sof} + C_D q_o$ (Equation 2-12). Obtain C_D from Section 2-15.3.3.

f. Construct positive phase pressure-time curve similar to Figure 2-195 (+).

Step 8. Determine negative phase of side wall loading.

a. Determine value of C_E^- and $t_{of}^-/W^{1/3}$ for the value of L_{wf}/L from Step 7a from Figures 2-196 (+) and 2-198 (+), respectively.

b. Calculate $P_r = C_E$ x P_{sof} and t_{of}.

c. Calculate rise time of negative phase equal to 0.25 t_{of} (Section 2-15.3.2).

d. Construct the negative pressure-time curve similar to Figure 2-195 (+).

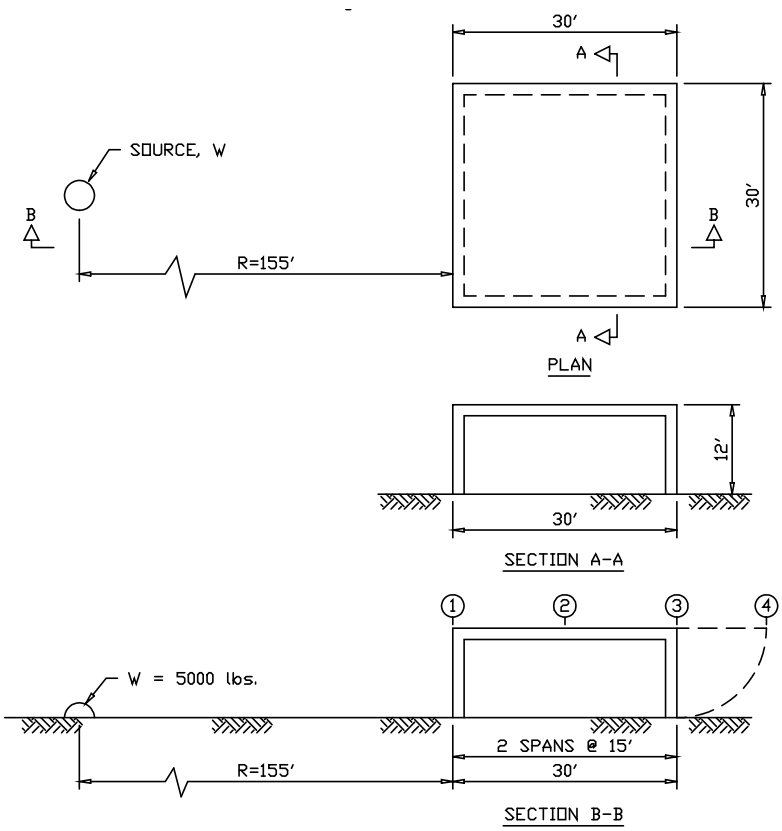
Step 9. Determine roof loading. Follow procedure outlined for side wall loading.

Step 10. Determine rear wall loading. Follow procedure outlined for side wall loading. For the purpose of calculations, assume that the back wall is rotated to a horizontal position (see Figure 2-199 (+)).

EXAMPLE 2A-10 EXTERNAL BLAST LOADS ON STRUCTURES

Required: Determine pressure-time blast loading curves for the front wall, roof, rear half of the side walls and rear wall of the structure shown in Figure 2A-9 (+) for a surface burst of 5,000 lbs at a distance from the front wall of 155 ft. Structure width is 30 ft and the shock front is plane.

Figure 2A-9



Step 1. Given: Charge weight = 5,000 lbs, R_G = 155 ft

Step 2. W = 1.2 (5,000) = 6,000 lbs

Step 3. Determine free-field blast wave parameters P_{so}, t_A, L_w and t_o at Points 1 through 3 and i_s at Point 1.

For Point 1 :

a. $$Z_G = \frac{R_G}{W^{1/3}} = \frac{155}{6000^{1/3}} = 8.53\,\text{ft/lb}^{1/3}$$

b. Determine free-field blast wave parameters from Figure 2-15 (+) for Z_G = 8.53 ft/lb$^{1/3}$

P_{so} = 12.8 psi

$t_A/W^{1/3}$ = 3.35 ms/lb$^{1/3}$

t_A = 3.35 (6000)$^{1/3}$ = 60.9 ms

$L_w/W^{1/3}$= 2.10 ft/lb$^{1/3}$

L_w = 2.10 (6000)$^{1/3}$ = 38.2 ft

$t_o/W^{1/3}$ = 2.35 ms/lb$^{1/3}$

t_o = 2.35 (6000)$^{1/3}$ = 42.7 ms

c. Determine incident impulse from Figure 2-15 (+) for Z_G = 8.53 ft/lb$^{1/3}$.

$$\frac{i_s}{W^{1/3}} = 9.0 \text{ psi - ms/lb}^{1/3}$$

$$i_s = 9.0(6000)^{1/3} = 163.5 \text{ psi - ms}$$

d. Repeat Steps 3a and 3b for Points 2 and 3. Results are tabulated below.

Point No.	R_G (ft)	Z_G (ft/lb$^{1/3}$)	P_{so} (psi)	$t_A/W^{1/3}$ (ms/lb$^{1/3}$)	t_A (ms)	$L_w/W^{1/3}$ (ft/lb$^{1/3}$)	L_w (ft)	$t_o/W^{1/3}$ (ms/lb$^{1/3}$)	t_o (ms)	$i_s/W^{1/3}$ (psi-ms/lb$^{1/3}$)	i_s (psi-ms)
1	155.0	8.53	12.8	3.35	60.9	2.10	38.2	2.35	42.7	9.00	163.5
2	170.0	9.35	10.8	3.90	70.9	2.24	40.7	2.48	45.1	-	-
3	185.0	10.18	9.0	4.60	83.6	2.35	42.7	2.62	47.6	-	-

Step 4. Determine front wall reflected pressure and impulse.

a. Read $C_{r\alpha}$ for P_{so} = 12.8 psi and α = 0° from Figure 2-193 (+) for Point 1.

$C_{r\alpha}$ = 2.70 then $P_{r\alpha} = C_{r\alpha} \times P_{so}$ = 2.70 x 12.8 = 34.6 psi

b. Read $i_{r\alpha}/W^{1/3}$ for P_{so} = 12.8 psi and α = 0° from Figure 2-194 (+/+) for Point 1.

$i_{r\alpha}/W^{1/3}$ = 17.0 then $i_{r\alpha}$ = 17.0 (6,000)$^{1/3}$ = 308.9 psi-ms

Step 5. Front wall loading, positive phase.

a. Calculate sound velocity in reflected overpressure region C_r from Figure 2-192 (+) for P_{so} = 12.8 psi.

C_r = 1.325 ft/ms

b. Calculate clearing time t_c from Equation 2-3:

$$t_c = \frac{4S}{(1+R)C_r} \qquad \text{(Equation 2-3)}$$

where:

S = 12.0 ft < 30/2

G = 30/2 = 15.0 ft > 12.0 ft

R = S/G = 12.0/15.0 = 0.80

then:

$$t_c = \frac{4 \times 12}{(1+0.80)1.325} = 20.1\,\text{ms}$$

c. Calculate t_{of} from Equation 2-11. Use impulse from Step 3c.

$$t_{of} = \frac{2i_s}{P_{so}} = \frac{2 \times 163.5}{12.8} = 25.5\,\text{ms}$$

d. Determine q_o from Figure 2-3 (+) for P_{so} = 12.8 psi.

q_o = 3.5 psi

e. Calculate $P_{so} + C_D q_o$:

C_D = 1.0 from Section 2-15.3.2

then,

$P_{so} + C_D q_o$ = 12.8 + (1.0 x 3.5) = 16.3 psi

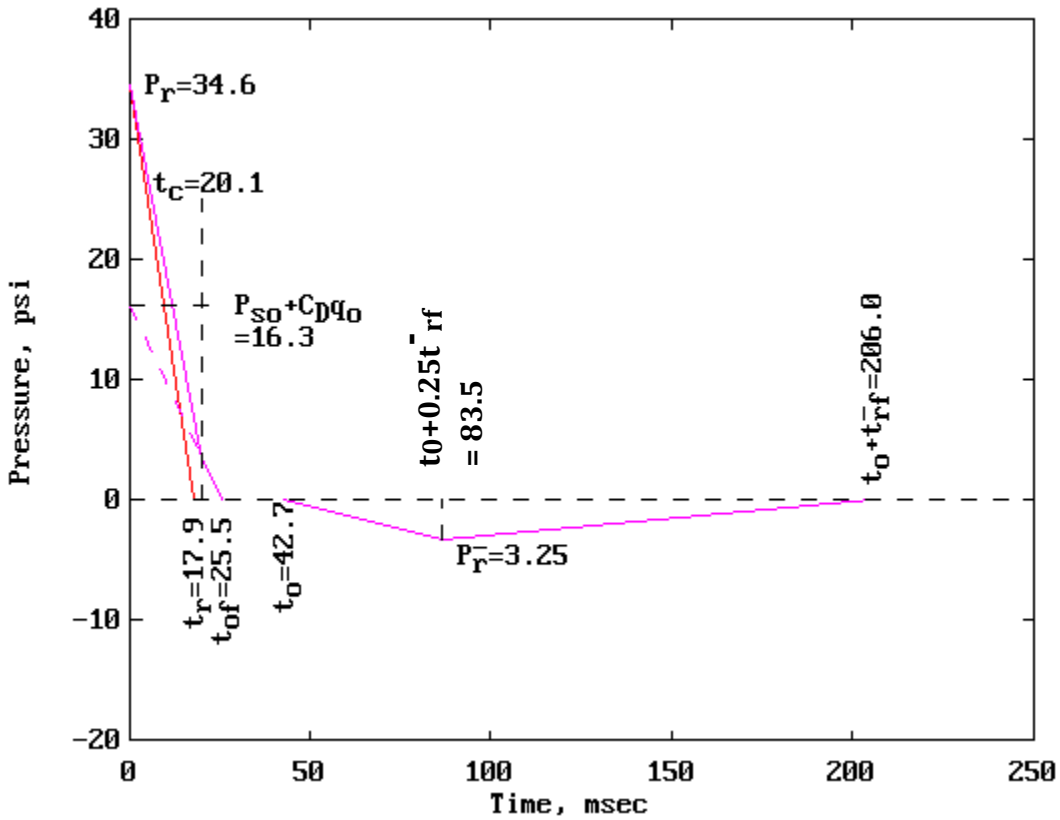
f. Calculate t_{rf} from Equation 2-11 and results of Step 4.

$$t_r = \frac{2i_{r\alpha}}{P_{r\alpha}} = \frac{2 \times 308.9}{34.6} = 17.9\,\text{ms}$$

g. Construct the pressure time curve. See Figure 2A-10 (+).

Note: The reflected pressure-time curve is used for design since the reflected impulse is less than the impulse produced by the clearing time.

Figure 2A-10



Step 6. Negative phase loading, front wall.

a. Read the values of Z corresponding to $P_{r\alpha}$ = 34.6 (Step 4a) and $i_{r\alpha}/W^{1/3}$ = 17.0 (Step 4b) from Figure 2-15 (+).

$P_{r\alpha}$ = 34.6 then Z ($P_{r\alpha}$) = 8.5

$i_{r\alpha}/W^{1/3}$ = 17.0 then Z ($i_{r\alpha}/W^{1/3}$) = 10.4

b. Using the Z values from Step 6a and Figure 2-16 (+) determine values of $P_{r\alpha}^-$ and $i_{r\alpha}^-$ (Peak pressure and impulse in negative phase).

$Z(P_{r\alpha})$ = 8.5 then, $P_{r\alpha}$ = 3.25 psi

$Z(i_{r\alpha}/W^{1/3})$ = 10.4 then, $i_{r\alpha}^-/W^{1/3}$ = 14.6 psi-ms/lb$^{1/3}$

and

$i_{r\alpha}$ = 14.6 x (6,000)$^{1/3}$ = 265.3 psi-ms

c. Calculate fictitious duration t_{rf}^{-}.

$$t_{rf}^{-} = \frac{2i_{r\alpha}^{-}}{P_{r\alpha}^{-}}$$

$$t_{rf}^{-} = \frac{2 \times 265.3}{3.25} = 163.3 \text{ ms}$$

d. Calculate negative phase rise time:

0.25 x t_{rf}^{-} = .25 x 163.3 = 40.8 ms

e. Construct the negative pressure-time curve.

t_o = 42.7 ms (Point 1, Step 3d)

t_o + 0.25 t_{rf}^{-} = 42.7 + 40.8 = 83.5 ms

t_o = t_{rf}^{-} = 42.7 + 163.3 = 206.0 ms

The negative pressure-time curve is plotted in Figure 2A-10 (+).

Step 7. Side wall loading, positive phase, calculate the loading on the rear-half of the wall (Point 2 to 3, Figure 2A-9 (+)).

a. Calculate L_{wf}/L ratio:

L = 15.0 ft (Point 2 to 3)

L_{wf} = 40.7 ft (Step 3d)

then,

L_{wf}/L = 40.7 / 15.0 = 2.71

b. Read $C_E, t_d/W^{1/3}$ and $t_{of}/W^{1/3}$ for L_{wf}/L = 2.71 and P_{sof} = 10.8 (Step 3d, Point 2)

C_E = 0.76	Figure 2-196 (+)
$t_d/W^{1/3}$ = .66	Figure 2-197 (+)
$t_{of}/W^{1/3}$ = 2.47	Figure 2-198 (+)

c. Calculate $C_E P_{sof}$, t_d and t_{of} using results of Step 7b.

$C_E P_{sof}$ = 0.76 x 10.8 = 8.2

t_r = 0.66 x (6,000)$^{1/3}$ = 12.0 ms

t_{of} = 2.47 x (6,000)$^{1/3}$ = 44.9 ms

d. Determine q_o from Figure 2-3 (+) for $C_E P_{sof}$ = 8.2 psi.

q_o = 1.55 psi

e. Calculate peak positive pressure from Equation 2-12.

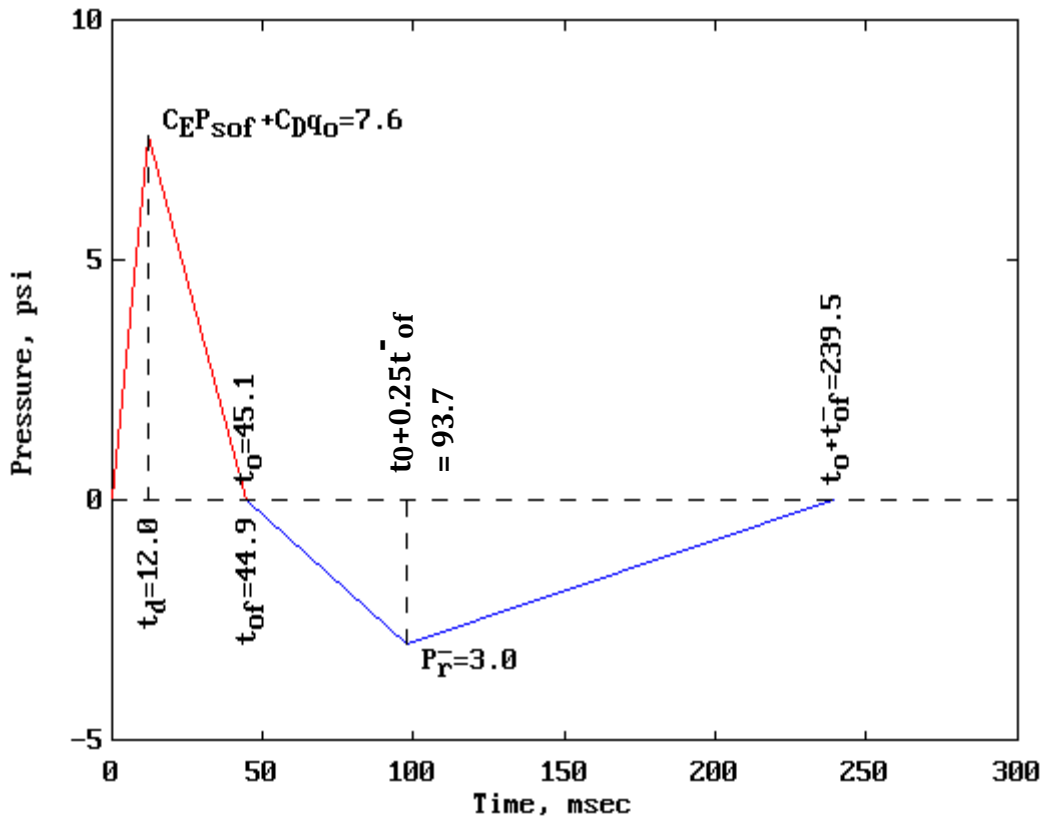
C_D = -0.40 from Section 2-15.3.2

$C_E P_{sof} + C_D q_o$ = 0.76 x 10.8 + (-0.40 x 1.55) = 7.6 psi

f. Construct the pressure-time curve.

See Figure 2A-11 (+) below.

Figure 2A-11



Step 8. Negative phase loading on the rear-half of the side wall.

a. Read values of C_E^- and $t_{of}^- /W^{1/3}$ for L_{wf} /L = 2.71 (Step 7a) from Figures 2-196 (+) and 2-198 (+) respectively.

C_E^- = 0.28

$t_{of}^- /W^{1/3}$ = 10.7 ms/lb$^{1/3}$

b. Calculate P_r^- and t_{of}^-:

$P_r^- = C_E^- \times P_{sof}$ = 0.28 x 10.8 = 3.0 psi

t_{of}^- = 10.7 x (6,000)$^{1/3}$ = 194.4 ms

c. Negative phase rise time:

0.25 t_{of}^- = 0.25 x 194.4 = 48.6ms

d. Construct the negative pressure-time curve.

t_o = 45.1 ms (Point 2, Step 3d)

t_o + 0.25 t_{of} = 45.1 + 48.6= 93.7ms

$t_o + t_{of}$ = 45.1 + 194.4 = 239.5 ms

The negative pressure-time curve is plotted in Figure 2A-11 (+).

Step 9. Calculate roof loading. (Point 1 to 3, Figure 2A-9 (+))

a. Calculate L_{wf}/L ratio:

L = 30.0 ft (Point 1 to 3)

L_{wf} = 38.2 ft (Step 3d) then,

L_{wf}/L = 38.2/30.0 = 1.27

b. Read C_E, $t_d /W^{1/3}$ and $t_{of} /W^{1/3}$ for L_{wf} /L = 1.27 and P_{sof} = 12.8 psi (Step 3d, Point 1) then,

C_E = 0.52	Figure 2-196 (+)
$t_d /W^{1/3}$ = 1.25	Figure 2-197 (+)
$t_{of} /W^{1/3}$ = 3.10	Figure 2-198 (+)

c. Calculate $C_E P_{sof}$, t_d and t_{of} using results of Step 9b.

$C_E P_{sof}$ = 0.52 x 12.8 = 6.66

t_d = 1.25 x (6,000)$^{1/3}$ = 22.7 ms

t_{of} = 3.10 x (6,000)$^{1/3}$ = 56.3 ms

d. Determine q_o from Figure 2-3 (+) for $C_E P_{sof}$ = 6.66 psi.

q_o = 1.05 psi

e. Calculate maximum pressure from Equation 2-12:

C_D = -0.40 from Section 2-15.3.2

$C_E P_{sof} + C_D q_o$ = 0.52 x 12.8 + (-0.40 x 1.05) = 6.24 psi

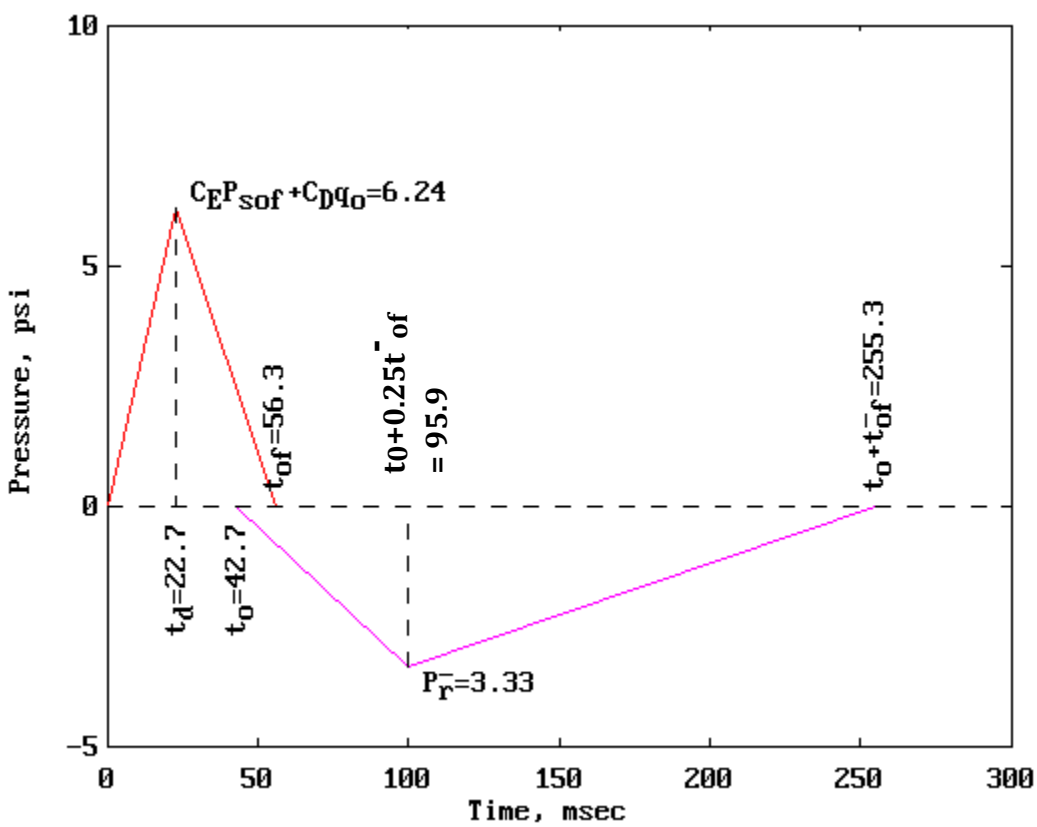
f. Construct the pressure-time curve. See Figure 2A-12 (+).

g. Read values of C_E^- and $t_{of}^-/W^{1/3}$ for L_{wf}/L = 1.27 (Step 9a) from Figures 2-196 (+) and 2-198 (+) respectively.

C_E^- = 0.26

$t_{of}^-/W^{1/3}$ = 11.7 ms/lb$^{1/3}$

Figure 2A-12



h. Calculate P_r^- and t_{of}^-:

$P_r^- = C_E^- \times P_{sof} = 0.26 \times 12.8 = 3.33$ psi

$t_{of}^- = 11.7 \times (6{,}000)^{1/3} = 212.6$ ms

i. Negative phase rise time:

$0.25\ t_{of}^- = 0.25 \times 212.6 = 53.2$ms

j. Construct the negative pressure-time curve.

$t_o = 42.7$ ms (Point 1, Step 3d)

$t_o + .25\ t_{of}^- = 42.7 + 53.2 = 95.9$ms

$t_o + t_{of}^- = 42.7 + 212.6 = 255.3$ ms

The negative pressure-time curve is plotted in Figure 2A-12 (+)

Step 10. Calculate rear wall loading (Point 3 to 4, Figure 2A-9 (+)). Assume rear wall is rotated to a horizontal position.

a. Calculate L_{wf}/L ratio:

$L = 12.0$ ft (Point 3 to 4 or height of the structure)

$L_{wf} = 42.7$ ft (Step 3d), then,

$L_{wf}/L = 42.7 / 12.0 = 3.56$

b. Read C_E, $t_d/W^{1/3}$ and $t_{of}/W^{1/3}$ for $L_{wf}/L = 3.56$ and $P_{sob} = 9.0$ psi (Step 3d, Point 3).

$C_E = 0.83$ Figure 2-196 (+)

$t_d/W^{1/3} = 0.51$ Figure 2-197 (+)

$t_{of}/W^{1/3} = 2.45$ Figure 2-198 (+)

c. Calculate $C_E P_{sob}$, t_r and t_o using results of Step 10b.

$C_E P_{sob} = 0.83 \times 9.0 = 7.47$ psi

$t_d = 0.51 \times (6{,}000)^{1/3} = 9.3$ ms

$t_{of} = 2.45 \times (6{,}000)^{1/3} = 44.5$ ms

d. Determine q_o from Figure 2-3 (+) for $C_E P_{sob} = 7.47$ psi

$q_o = 1.30$ psi

e. Calculate maximum pressure from Equation 2-12:

C_D = -0.40 from Section 2-15.3.2

$C_E P_{sob} + C_D q_o$ = 0.83 x 9.0 + (-0.40 x 1.30) = 6.95 psi

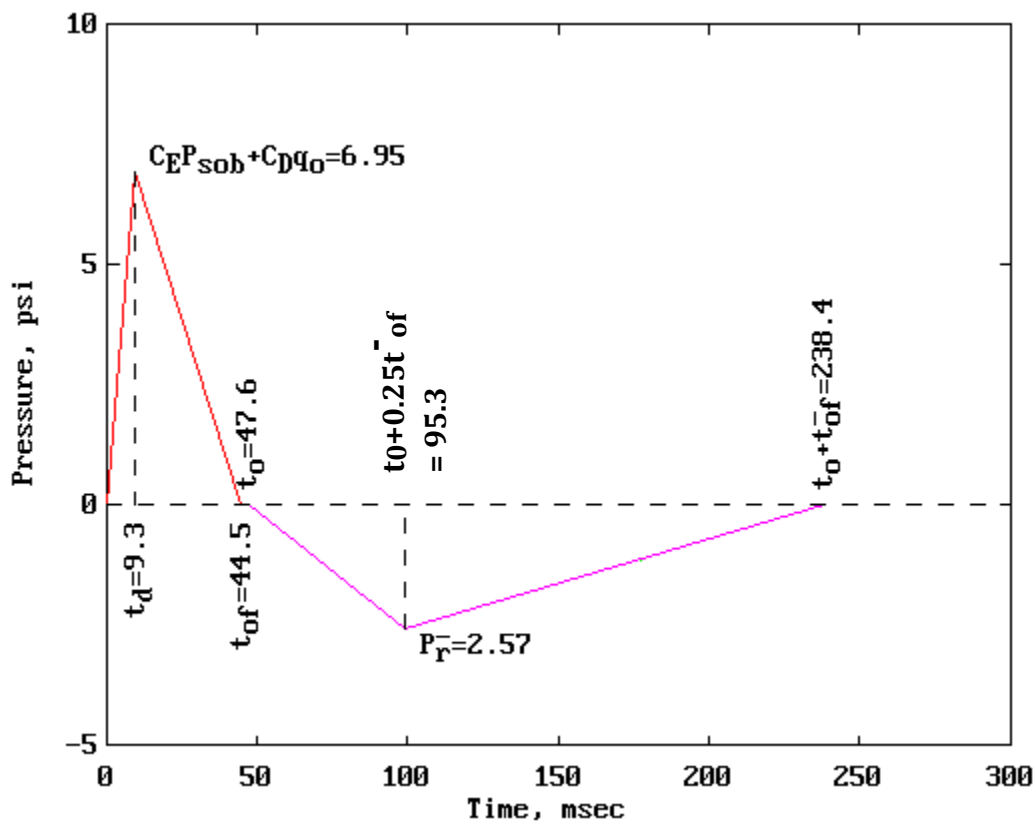
f. Construct the pressure-time curve. See Figure 2A-13 (+).

g. Read values of C_E^- and $t_{of}^-/W^{1/3}$ for L_{wf}/L = 3.56 (Step 10a) from Figures 2-196 (+) and 2-198 (+) respectively.

C_E^- = .285

$t_{of}^-/W^{1/3}$ = 10.5 ms/lb$^{1/3}$

Figure 2A-13



h. Calculate P_r^- and t_{of}^-:

$P_r^- = C_E^- \times P_{sob}$ = .285 x 9.0 = 2.57 psi

t_{of}^- = 10.5 x (6,000)$^{1/3}$ = 190.8 ms

i. Negative phase rise time:

$0.25\ t_{of}^{-} = .25 \times 190.8 = 47.7\text{ms}$

j. Construct the negative pressure-time curve.

$t_o = 47.6$ ms (Point 3, Step 3d)

$t_o + 0.25\ t_{of} = 47.6 + 47.7 = 95.3\text{ms}$

$t_o + t_{of} = 47.6 + 190.8 = 238.4$ ms

The negative pressure-time curve is plotted in Figure 2A-13 (+).

PROBLEM 2A-11 BLAST LOADS ON A STRUCTURE WITH FRONT WALL OPENINGS

Problem: **Determine the pressure-time loads acting on the exterior front wall and all interior surfaces of a rectangular structure with front wall openings due to an external shock load.**

Step 1. Charge weight:

a. Determine TNT equivalent charge weight, *W.*

b. Increase charge weight by 20% safety factor, $W = 1.20 \times W$.

c. Determine charge weight scaling factor, $W^{1/3}$.

Step 2. Determine free field blast parameters:

a. For an air burst, use Problem 2A-2 procedure; for a surface burst, use Problem 2A-3 procedure; for leakage pressures, use Problem 2A-8 or 2A-9 procedures.

b. Evaluate the angle of incidence, α, as the angle between the ground distance from the charge to the center of the front wall, and the normal distance from the charge to the front wall.

Step 3. Front wall idealized pressure-time blast loads:

A. Exterior Blast Load:

a. Determine peak positive reflected pressure, P_r, as a function of P_{so} and α, using Figure 2-193 (+).

b. Determine peak positive reflected scaled unit impulse, $i_{r\alpha}/(W^{1/3})$, as a function of P_{so} and α, using Figure 2-194 (+/+).

c. Determine the absolute positive reflected impulse by multiplying the scaled unit impulse by $W^{1/3}$.

d. Determine the sound velocity of the reflected pressure wave, C_r, as a function of P_{so}, using Figure 2-192 (+).

e. Determine the reflected pressure clearing time, T'_c, from Equation 2-14.

f. Construct the exterior blast pressure-time load. Follow the procedure in Problem 2A-10.

g. Determine the scaled wave length of the incident wave, $L_w/(W^{1/3})$ as a function of P_{so}, using Figure 2-15 (+), irrespective of how the external incident wave was created.

h. Determine the absolute wave length by multiplying the scaled wave length by $W^{1/3}$.

B. Interior Blast Load:

a. Determine the following parameters: L_w/L, L_w/H, A_o/A_w, W/H, and L/H, where A_o is the total area of openings in the front wall, and A_w is the area H by W.

b. Determine the idealized factored average peak pressure, P_{max} x (L_w/H), as a function of W/H, P_{so}, A_o/A_w, and L_w/H, using Figures 2-203 (+) to 2-206 (+). Calculate P_{max} = (P_{max} x L_w/H)/(L_w/H).

c. Determine the arrival time, T_1, as a function of W/H, P_{so}, and A_o/A_w, using Figures 2-207 (+/+) and 2-208 (+/+).

d. Determine the rise time, T_2 - T_1, as a function of W/H, P_{so}, and L_w/H, from Figures 2-209 (+/+) and 2-210 (+/+).

e. Determine the duration time, T_3 - T_1, as a function of W/H, P_{so}, and L_w/H, from Figures 2-211 (+/+) and 2-212 (+/+).

f. Using times T_1, T_2 - T_1, T_3 - T_1, and P_{max}, construct the idealized pressure-time blast load. See Figure 2-201a (+) for general configuration of this blast load.

Step 4. Side Wall Idealized Interior Pressure-Time Blast Load:

a. Determine the maximum average sidewall pressure, P_{max}, from Equation 2-15.

b. Determine the idealized times T_1 and T_2 for W/H, using Figure 2-213 (+/+).

c. Determine the idealized times T_3 and T_4 for W/H, using Figures 2-214 (+/+) to 2-229 (+/+).

d. Using times T_1, T_2, T_3, T_4, and P_{max}, construct the idealized pressure-time load. See Figure 2-201b (+) for general configuration of this blast load.

Step 5. Back Wall Idealized Interior Pressure-Time Blast Load:

a. Determine the maximum average positive reflected pressure coefficient, P_{RIB}/P_{so}, as a function of L/H, P_{so}, and A_o/A_w, using Figures 2-233 (+/+) and 2-234 (+).

b. Determine the maximum average pressure, P_{RIB}, by multiplying the pressure coefficient, P_{RIB}/P_{so}, by P_{so}.

c. Determine the idealized time T_1 as a function of W/H, P_{so}, L/H and A_o/A_w, using Figure 2-230 (+/+).

d. Determine the idealized pressure duration, T_2 - T_1, as a function of P_{so} and A_o/A_w, using Figure 2-232 (+/+).

e. Using times T_1, T_2 - T_1, and P_{RIB}, construct the idealized pressure-time blast load. See Figure 2-201c (+) for general configuration of this blast load.

Step 6. Roof Idealized Interior Pressure-Time Blast Load:

a. Determine the W/H ratio for the roof as the inverse of W/H ratio of the side wall.

b. Repeat Step 4 using the W/H ratio of the roof.

EXAMPLE 2A-11 BLAST LOADS ON A STRUCTURE WITH FRONT WALL OPENINGS

Required: For the structure and charge as is shown in Figure 2A-14 (+), determine the idealized positive external blast load on the front wall, and the idealized positive internal blast load on the front wall, side wall, roof and back wall.

Step 1. Charge weight

a. W = 5000 lbs TNT

b. W = 1.20 x 5000 = 6000 lbs TNT

c. $W^{1/3}$ = 18.1712 $\text{lbs}^{1/3}$

Step 2. Free field blast parameters - surface burst

a. Procedure from Problem 2A-3.

Blast parameters: P_{so}, U, i_s, t_o, t_A for W = 6000 lbs, R_G = 155 ft

$Z_G = R_G/W^{1/3}$ = 155/18.1712 = 8.53 (say 8.5)

From Figure 2-15 (+) for hemispherical surface burst

$P_{so} = f_1(Z_G)$ = 12.6 psi

$U = f_2(Z_G)$ = 1.46 ft/ms

$i_s/W^{1/3}\ f_3(Z_G)$ = 9.0 psi-ms/$\text{lb}^{1/3}$, i_s = 163.54 psi-ms

$t_o/W^{1/3} = f_4(Z_G)$ = 2.40 ms/$\text{lb}^{1/3}$, t_o = 43.61 ms

$t_A/W^{1/3} = f_5(Z_G)$ = 3.40 ms/$\text{lb}^{1/3}$, t_A = 61.78 ms

b. Charge to wall center ground distance = 155.0 ft

Charge to wall normal distance = 155.0 ft

$\alpha = \cos^{-1}(155/155) = 0°$

Figure 2A-14

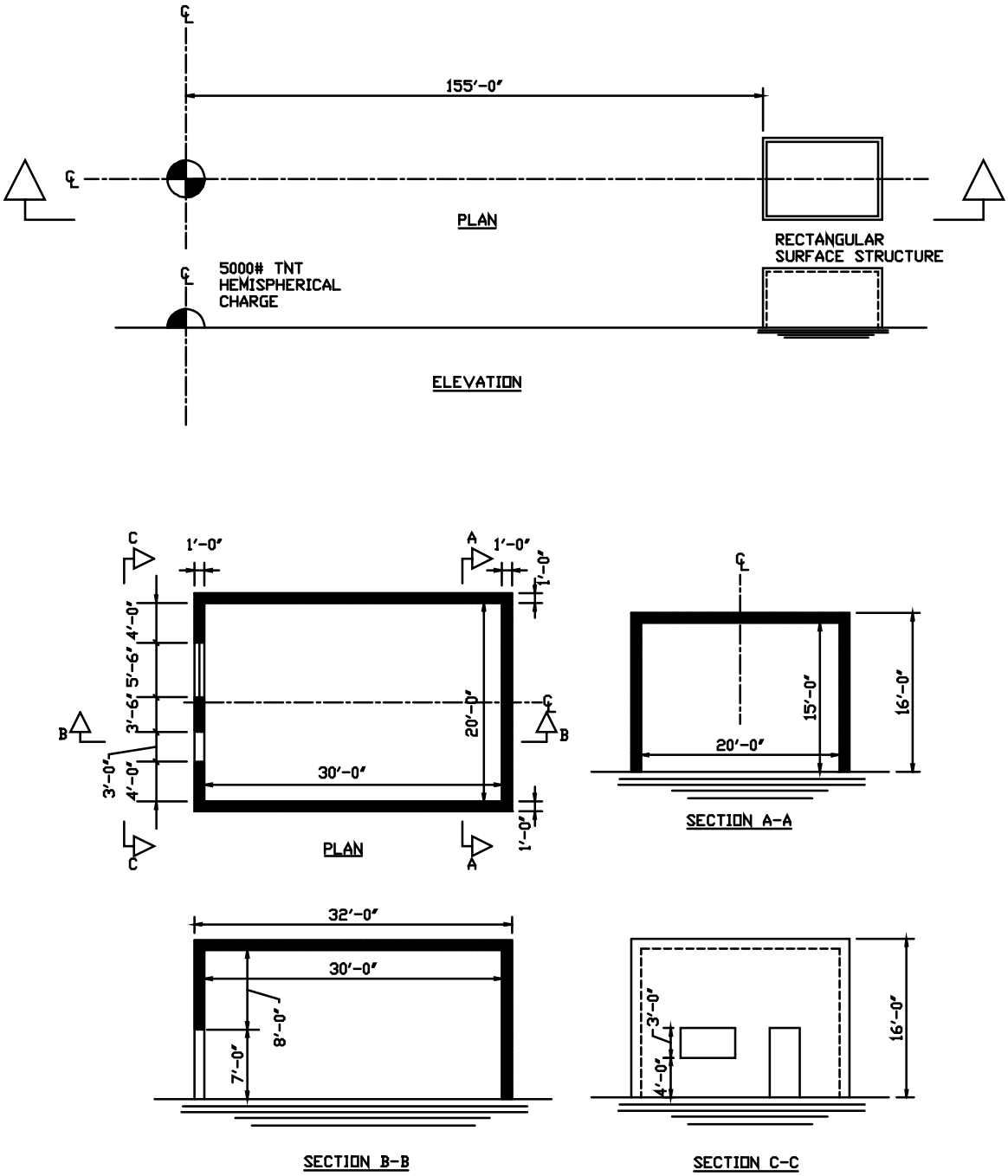
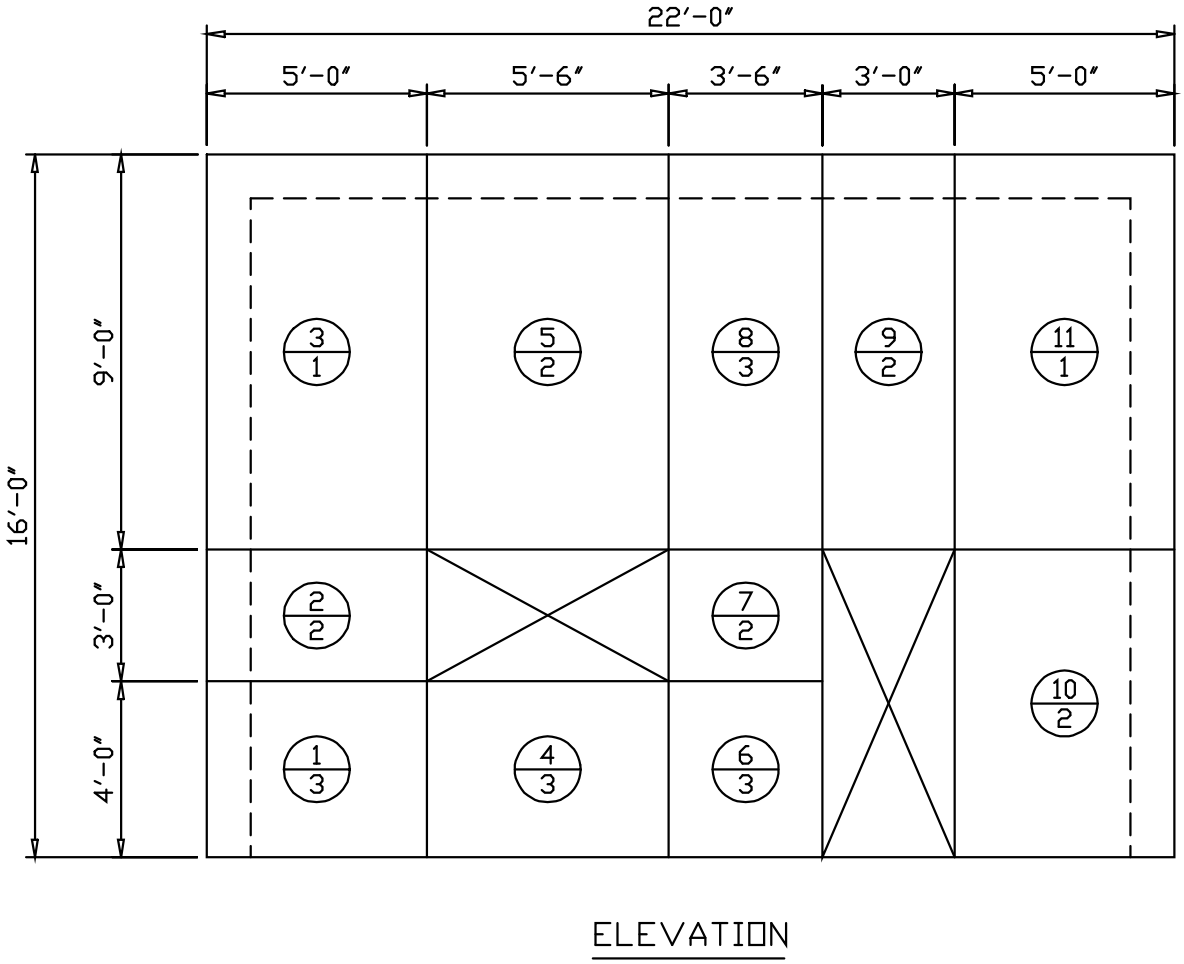
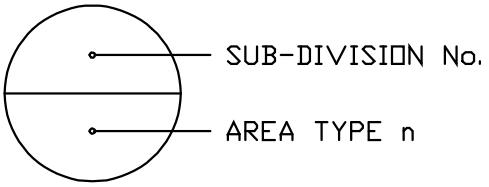

155′-0″
PLAN
RECTANGULAR
SURFACE STRUCTURE
5000# TNT
HEMISPHERICAL
CHARGE
ELEVATION
1′-0″
4′-0″
5′-6″
3′-6″
3′-0″
4′-0″
20′-0″
30′-0″
PLAN
15′-0″
16′-0″
20′-0″
SECTION A-A
32′-0″
30′-0″
8′-0″
7′-0″
SECTION B-B
3′-0″
4′-0″
16′-0″
SECTION C-C

Figure 2A-15



WALL SUB-DIVISION NOMENCLATURE



Step 3. Front wall idealized pressure-time blast load

A. Exterior Blast Load

a. From Figure 2-193 (+), for $\alpha = 0°$ and P_{so} = 12.6 psi, determine

$C_{r\alpha} = P_{r\alpha}/P_{so}$

P_{so}	10.0	12.6	20.0
$C_r\alpha$	2.40	?	2.90

$C_{r\alpha}$ = (2.9 - 2.4) x (12.6 - 10.0) / (20.0 - 10.0) + 2.40

= 0.130 + 2.40 = 2.53

$P_{r\alpha} = C_{r\alpha}$ x P_{so} = 2.53 x 12.6 = 31.878 psi, say 31.9 psi

b. From Figure 2-194 (+/+), for $\alpha = 0°$, read $i_{r\alpha}/W^{1/3}$ for P_{so} = 10 and 20 psi and interpolate for $i_{r\alpha}/W^{1/3}$ at P_{so} = 12.6 psi

P_{so} (psi)	**$i_{r\alpha}/W^{1/3}$ (psi-ms/lb$^{1/3}$)**
10	15.2
12.6	?
20	23

$i_{r\alpha}/W^{1/3}$ = (23.0 - 15.2) x (12.6 - 10.0)/(20.0 - 10.0) + 15.2

= 2.028 + 15.2 = 17.228 psi-ms/lb$^{1/3}$

c. Determine absolute impulse,

$i_{r\alpha} = (i_{r\alpha}/W^{1/3})$ x $(W^{1/3})$ = 17.228 x 18.1712 = 313.1 psi-ms

d. For P_{so} = 12.6 psi, C_r = 1.325 ft/ms from Figure 2-192 (+).

e. Using Figure 2A-15 (+) as the front wall sub-divisioning, determine h_n, W_n, δ_n, h'_n, A_n, $\delta_n h'_n A_n$, $\Sigma \delta_n h'_n A_n$, A_f, S', S, R, and T'_c.

Subdivision No.	Type n	δ_n -	h'_n (ft)	h_n (ft)	W_n (ft)	A_n (ft^2)	$\delta_n h'_n A_n$ (ft^3)
1	3	1.0	5.0	4.0	5.0	20.0	100.0
2	2	0.50	5.0	3.0	5.0	15.0	37.50
3	1	1.0	5.0	9.0	5.0	45.0	225.0
4	3	1.0	4.0	4.0	5.5	22.0	88.0
5	2	0.50	9.0	9.0	5.5	49.50	222.750
6	3	1.0	3.50	4.0	3.5	14.0	49.0
7	2	0.50	3.50	3.0	3.5	10.5	18.375
8	3	1.0	9.0	9.0	3.5	31.5	283.50
9	2	0.50	9.0	9.0	3.0	27.0	121.50
10	2	0.50	5.0	7.0	3.0	35.0	87.50
11	1	1.0	5.0	9.0	3.0	45.0	225.0
						$\Sigma\ \delta_n h'_n A_n$ =	**1458.125**

A_f = (16 x 32) - (3 x 5.5) - (7.0 x 3.0)

= 512 - 16.5 - 21.0

= 512 - 37.5

= 474.5 ft^2

$$S' = \left(\sum_{1}^{11} \delta_n h'_n A_n\right) / A_f = 1458.125 / 474.5 = 3.073\ ft$$

H = 15.0 ft, W = 20.0 ft, $H < W$

$S = H$ = 15.0 ft, $S' < S$ O.K.

$W > H$

$G = W$ = 20.0 ft

$R = S/G$ = 15.0/20.0 = 0.75; C_r = 1.325 ft/ms

$t'_c = 4S'/[(1 + R) \times C_r]$ = (4 x 3.073)/(1.75 x 1.325) = 5.301 ms

f. Following general procedure Problem 2A-10, Step 5, required previously determined values are:

P_{so} = 12.6 psi

i_s = 163.5 psi-ms

$P_{r\alpha}$ = 31.9 psi

$i_{r\alpha}$ = 313.1 psi-ms

Determine

$t_{of} = 2i_s / P_{so}$ = 2 x 163.5/12.6 - 26 ms, Equation 2-6

$t_{rf} = 2i_{r\alpha}/P_{r\alpha}$ = 2 x 313.1/31.9 - 19.6 ms, Equation 2-11

$q_o = f(P_{so})$ = 3.4 psi, Figure 2-3 (+)

C_D = 1.0, Section 2-15.3.2,

$P_{so} + C_D q_o$ = 16 psi, Section 2-15.3.2

Construct infinite surface impulse and theoretic bilinear actual surface impulse. Minimum value is design impulse.

Infinite surface fictitious impulse = $i_{r\alpha}$ = 313.1 psi-ms

Bi-linear theoretic actual surface impulse is area under curve $P_{r\alpha}$ to t'_c on line $P_{so} + C_D q_o$ to t_{of}

Let $P = (P_{so} + C_D q_o)\,[1 - (t'_c / t_{of})]$

$= 16.0\,[1 - (5.3/26)] = 12.7$ psi

$i_{BL} = [(P_{r\alpha} - P)(t'_c/2)] + (Pt'_c) + [(t_{of} - t'_c)(P/2)]$

$= [(31.9 - 12.7)(5.3/2)] + (12.7 \times 5.3)$

$+ [(26 - 5.3)(12.7/2)]$

$= 50.9 + 67.3 + 131.4$

$= 250$ psi-ms

$i_{BL} < i_{r\alpha}$, use bi-linear pressure-time as design blast load.

See Figure 2A-16 (+).

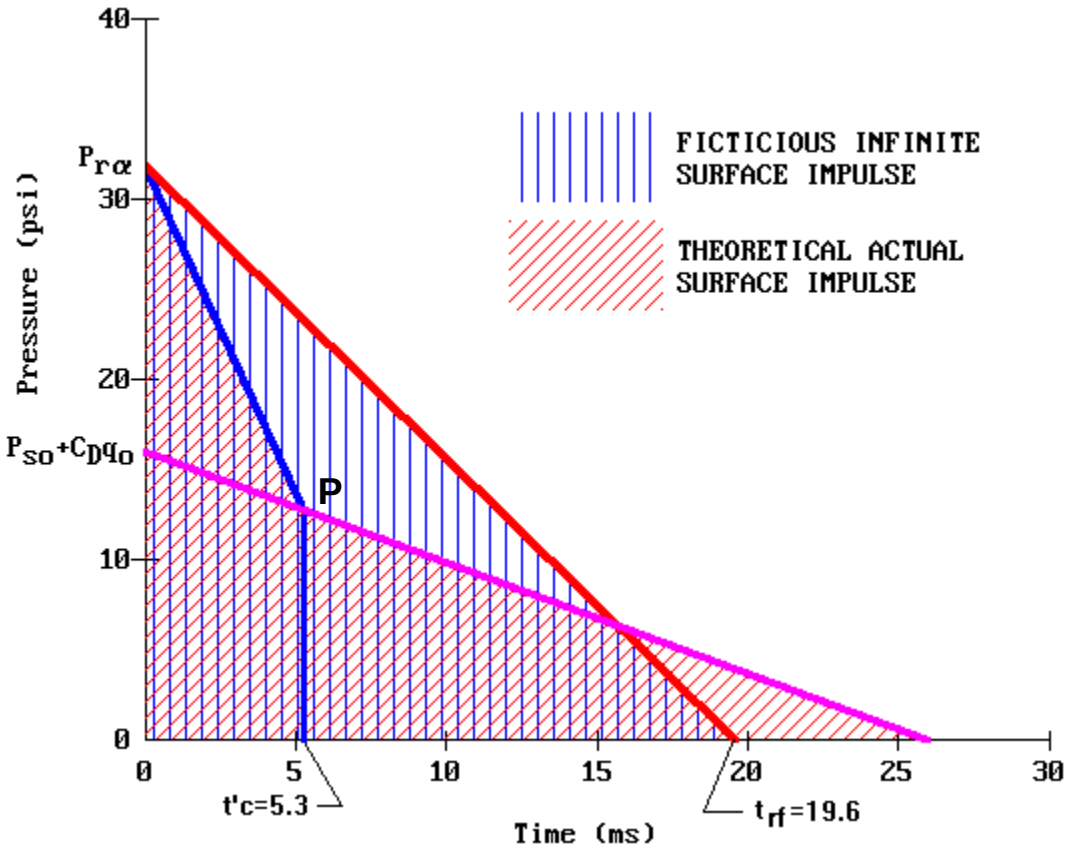
g. For P_{so} = 12.6 psi, $L_w / W^{1/3}$ = 2.10 ft/lb$^{1/3}$, Figure 2-15 (+)

h. $L_w = (L_w / W^{1/3})(W^{1/3})$ = 2.10 x 18.1712 = 38.16, say 38.2 ft

B. Interior Blast Load

a. From previous steps: L_w = 38.2 ft, L = 30 ft, H = 15 ft, W = 20 ft

Figure 2A-16



A_o = Door opening area + window opening area

= (7 x 3) + (3 x 5.5) = 37.5 ft^2

$A_w = H \times W$ = 15 x 20 = 300 ft^2

A_o/A_w = 37.5/300 = 0.125

L_w/L = 38.2/30 = 1.27

L_w/H = 38.2/15 = 2.54

W/H = 20/15 = 1.33

L/H = 30/15 = 2.00

b. For W/H = 1.33, P_{so}= 12.6 psi, A_o/A_w = 0.125, and L_w/H = 2.54, summarize factored maximum average pressure, P_{max} x L_w/H, for W/H and L_w/H equal to 0.75, 1.5, 3 and 6.

Figure No.	W/H	L_w/H	P_{max} x L_w/H
2-203 (+)	0.75	0.75	15.0
		1.50	38.5
		3.0	88.0
		6.0	190.0
2-204 (+)	1.50	0.75	4.70
		1.50	17.0
		3.0	55.0
		6.0	131.0
2-205 (+)	3.0	0.75	2.0
		1.50	7.0
		3.0	27.0
		6.0	85.0
2-206 (+)	6.0	0.75	1.0
		1.50	3.20
		3.0	10.0
		6.0	35.0

Plot Figure 2A-17a (+), and interpolate to determine P_{max} x L_w/H at L_w/H = 2.54 for W/H = .75, 1.5, 3 and 6.

W/H	0.75	1.5	3	6
P_{max} x L_w/H	74	44	19	7.5

Plot Figure 2A-17b (+) from above values, and interpolate to determine P_{max} x L_w/H = 48 for W/H = 1.33.

Determine P_{max} = (P_{max} x L_w/H)/(L_w/H) = 48/2.54 = 18.9 psi.

c. For P_{so} = 12.6 psi and A_o/A_w = 1/8, determine T_1 for W/H = 0.75, 1.5, and 3 from Figures 2-207 (+/+) and 2-208 (+/+)

W/H	0.75	1.5	3
T_1	1.25	1.70	2.26

Plot Figure 2A-18 (+) with above values, and determine T_1 = 1.60 for W/H = 1.33.

d. For P_{so}= 12.6 psi, determine T_2 - T_1 for W/H and L_w/H = 0.75, 1.5, and 3, from Figures 2-209 (+/+) and 2-210 (+/+)

W/H	0.75			1.5			3		
L_w/H	0.75	1.5	3	0.75	1.5	3	0.75	1.5	3
T_2 - T_1	2.07	2.07	2.07	4.70	6.20	7.0	6.50	10.8	15.0

Plot Figure 2A-19 (+/+) with above values, and interpolate to determine T_2 - T_1 at L_w/H = 2.54 for W/H = 0.75, 1.5 and 3, as summarized below.

W/H	0.75	1.5	3
T_2 - T_1	2.07	6.75	14.0

Plot Figure 2A-19 (+/+) with above values, and determine T_2 - T_1 = 5.80 ms for W/H = 1.33.

e. For P_{so}= 12.6 psi, determine T_3 - T_1 for W/H = 0.75, 1.5, and 3 and L_w/H = 0.75, 1.5, and 3, from Figures 2-211 (+/+) and 2-212 (+/+), as summarized in the following figures.

Figure 2A-17a

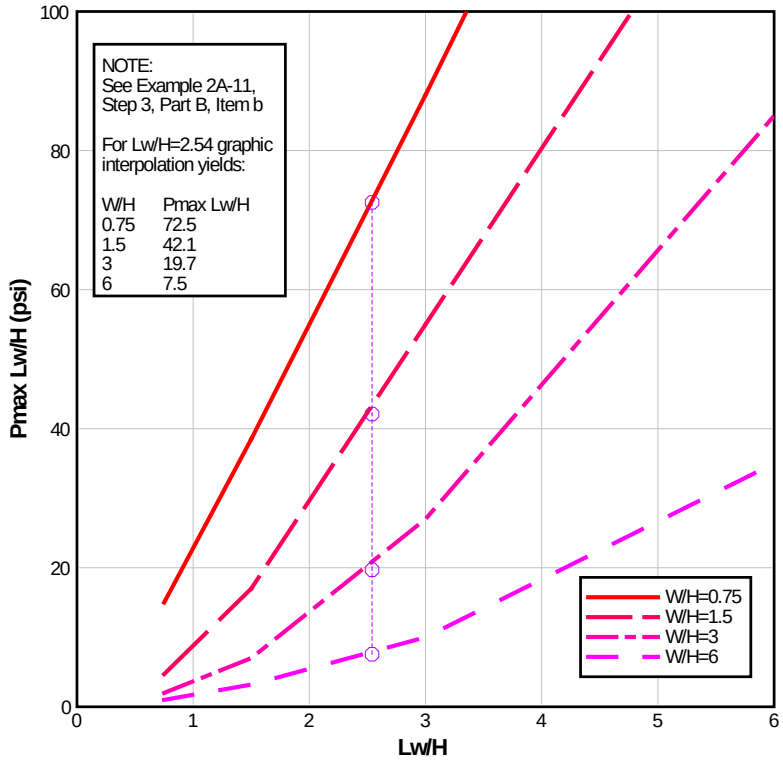


Figure 2A-17b

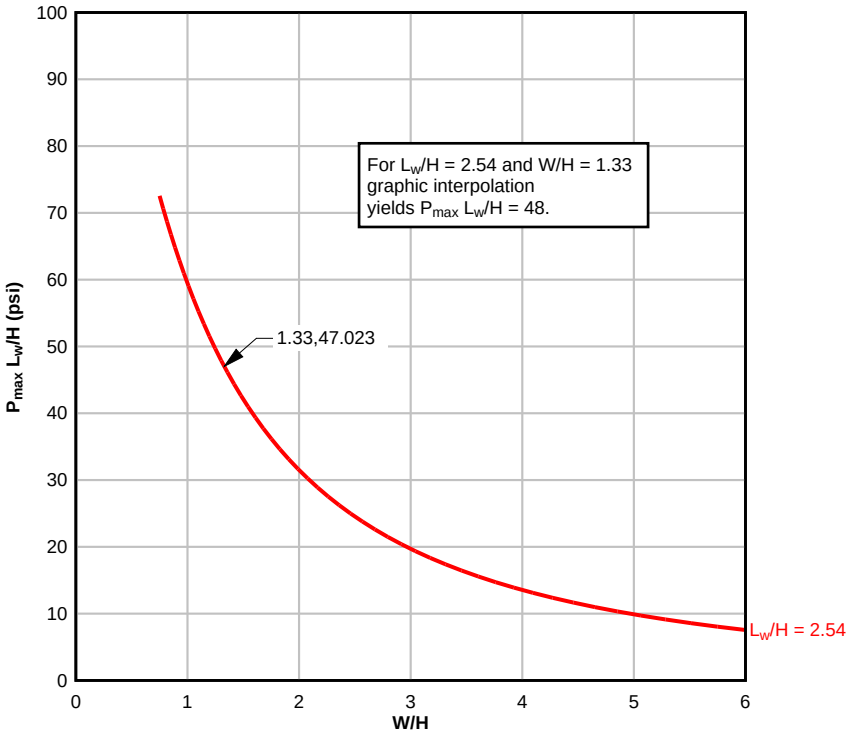


Figure 2A-18

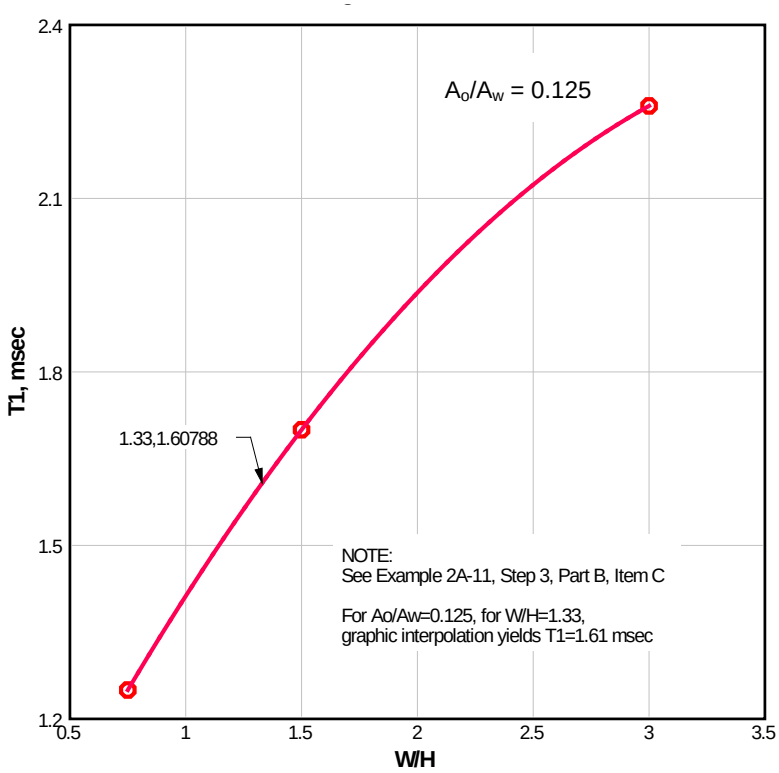

2.4
2.1
1.8
1.5
1.2
T1, msec
0.5
1
1.5
2
2.5
3
3.5
W/H
A_o/A_w = 0.125
1.33,1.60788
NOTE:
See Example 2A-11, Step 3, Part B, Item C
For Ao/Aw=0.125, for W/H=1.33,
graphic interpolation yields T1=1.61 msec

Figure 2A-19a

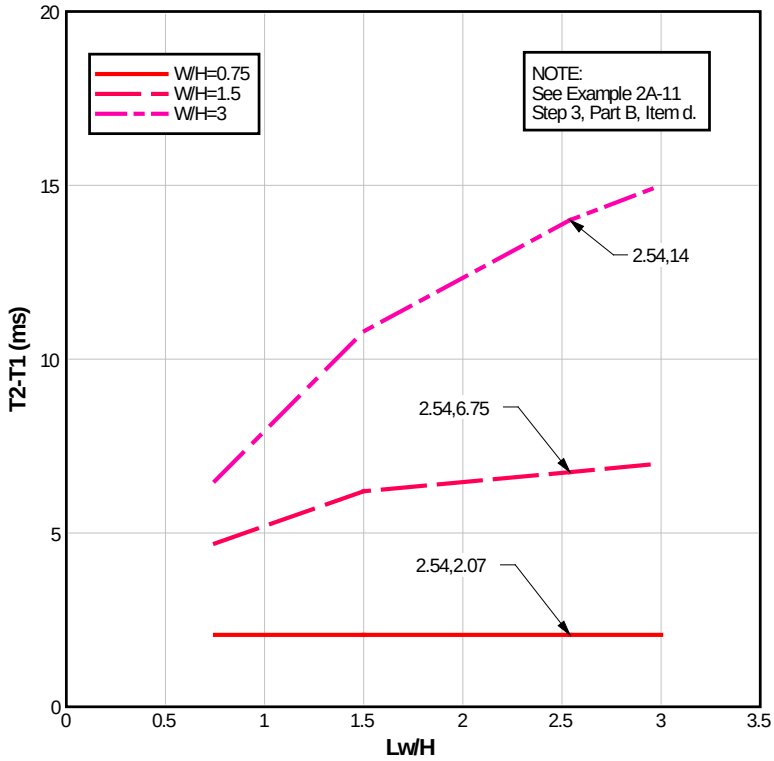
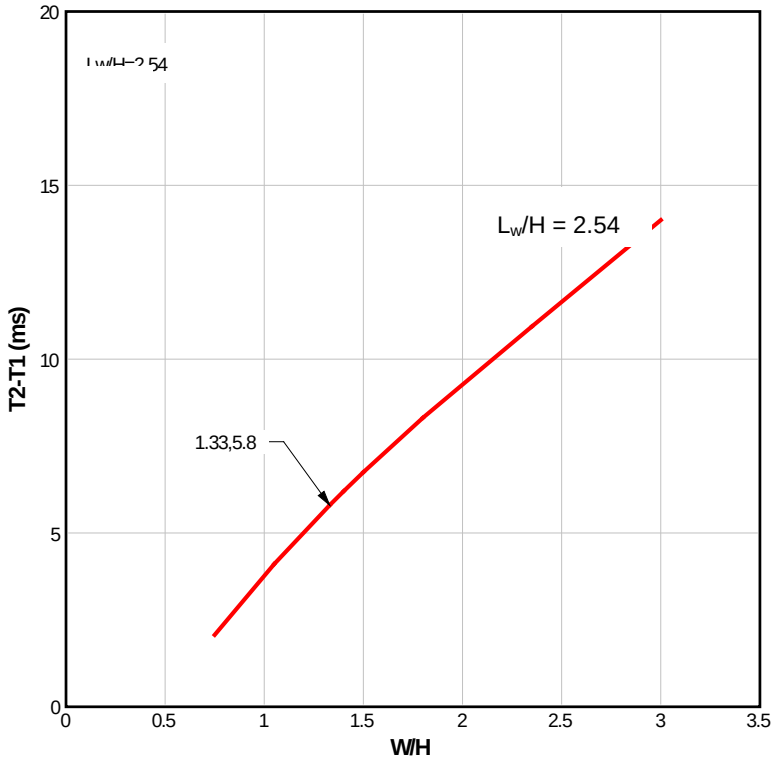


Figure 2A-19b



W/H	0.75			1.5			3		
L_w/H	0.75	1.5	3	0.75	1.5	3	0.75	1.5	3
T_3 - T_1	5.2	8.2	14.5	10.0	13.5	19.5	18.6	24.8	34.8

Plot Figure 2A-20 (+/+) with above values, and graphically interpolate to determine T_3 - T_1 at L_w /H = 2.54 for W/H = 0.75, 1.5, and 3, as summarized below.

W/H	0.75	1.5	3
T_3 - T_1	12.8	17.5	31.7

Plot Figure 2A-20 (+/+) with above values, and determine T_3 - T_1 = 16.3 ms at W/H = 1.33.

Figure 2A-20a

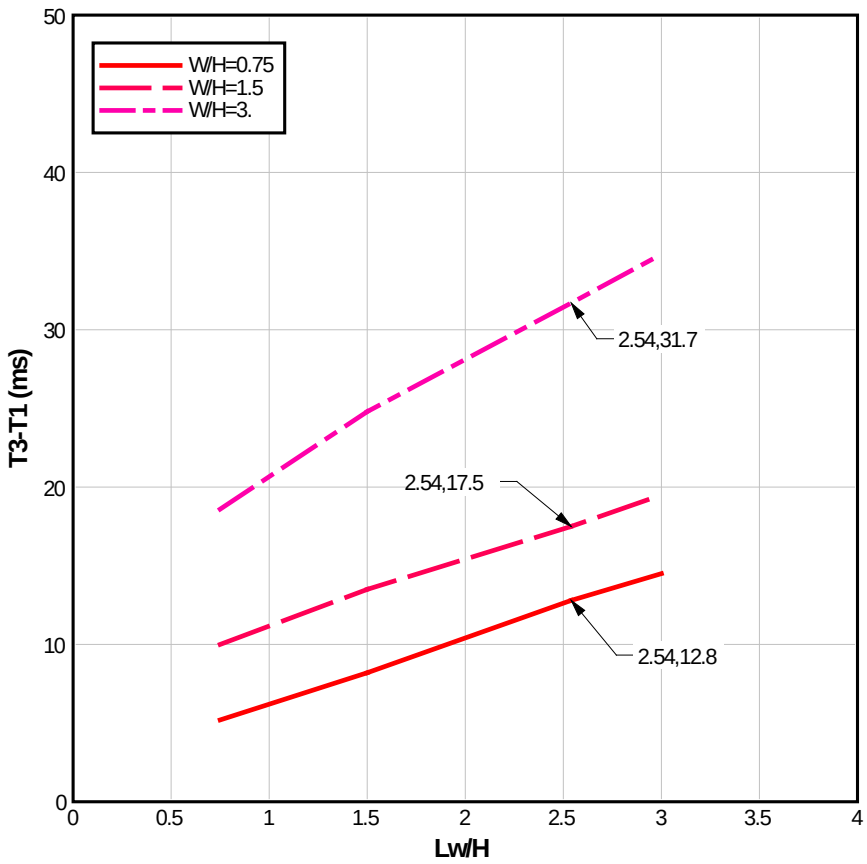
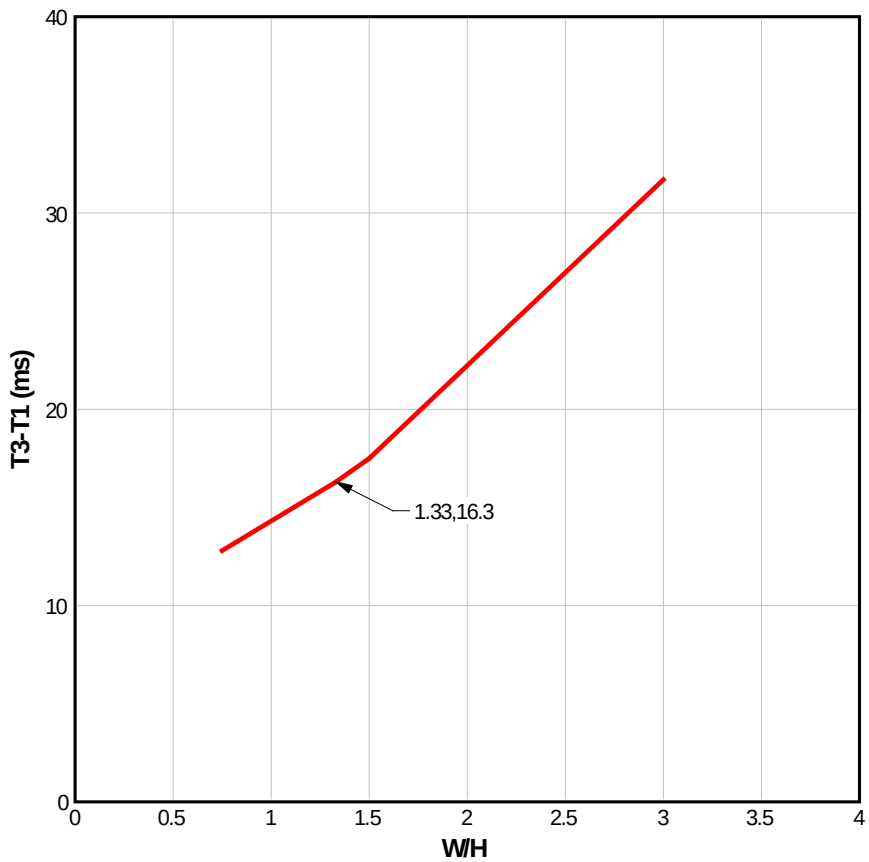


Figure 2A-20b



f. Determine times T_2 and T_3 from T_1, T_2 - T_1, and T_3 - T_1.

T_1 = 1.60 ms

T_2 - T_1 = 5.80 ms

T_3 - T_1 = 16.30 ms

T_2 = 5.80 + 1.60 = 7.40 ms

T_3 = 16.30 + 1.60 = 17.9 ms

Plot Figure 2A-23 (+) using above values and P_{max} = 18.9 psi.

Step 4. Sidewall idealized interior pressure-time blast load.

a. Using Equation 2-15, with P_{so}= 12.6 psi, A_o/A_w = 1/8, L_w/L = 1.27, L/H = 2.0, solve for P_{max} for W/H = 0.75, 1.5 and 3.

Equation 2-15: $P_{max} = K/(L_w/L)$

For W/H = 0.75, $K = A \times B \times C^E \times F^H \times P_{so}^{0.9718}$, where:

$A = [0.5422\ (L_w/L)^{1.2944}] - 0.001829 = 0.7385$

$B = [0.654 + 2.616\ (A_o/A_w) - 4.928\ (A_o/A_w)\ ]^2$

$\times\ [2.209\ (L/H)^{-0.3451} - 0.739] = 0.9040$

$C = [0.829 + 0.104\ (L_w/L)^{1.6}] + [0.00124$

$+\ 0.00414\ (L_w/L)^{3.334}] \times [L/H]^D = 1.0388$

$D = 2.579 - 0.0534\ (L_w/L)^{3.891} = 2.4428$

$E = 999\ (A_o/A_w)^{9.964} = 0.000001002$

$F = 1.468 - 1.6627\ (A_o/A_w)^{0.7801} + [1.8692$

$-\ 1.1735\ (A_o/A_w)^{-0.2226}] \times (L_w/L)^G = 1.1592$

$G = 0.2979\ (A_o/A_w)^{-1.4872} - 0.8351 = 5.7286$

$H = (5.425 \times 10^{-4}) + (1.001 \times 10^{-3})\ (L/H)^{9.965} = 0.0005435$

$K = 0.7385 \times 0.9040 \times 1.0388^{0.000001002} \times 1.1592^{0.0005435}$

$\times\ 12.6^{0.9718} = 7.83$

$P_{max} = 7.83/1.27 \approx 6.2$ psi, for W/H = 0.75

For $1.5 \leq W/H \leq 6$, $K = [A + [B \times (L_w/L)^C]] \times D \times E \times P_{so}^{1.025}$ where,

$A = 0.002\ (W/H)^{1.4467} - 0.0213$

$B = 2.2075 - (1.902\ (W/H)^{-0.085})$

$C = 1.231 + (\ 0.0008\ (W/H)^{2.678}\ )$

$D = (2.573\ (L/H)^{-0.444}) - 0.3911$

$E = 0.4221 + (1.241\ (A_o/A_w\ )^{0.367})$

For W/H = 1.5, 3 and 6, determine values for A to E, and K and P_{max}, as summarized below.

W/H	*A*	*B*	*C*	*D*	*E*	*K*	P_{max}
1.5	-0.0177	0.3700	1.2334	1.5003	1.0006	9.6743	7.60
3	-0.0115	0.4751	1.2462	1.5003	1.0006	12.690	9.98

Plot Figure 2A-21 (+/+/+/+) with above values of P_{max} vs. W/H = 0.75, 1.5 and 3, and determine P_{max} = 7.30 psi for W/H = 1.33.

b. For P_{so} = 12.6 psi, determine T_1 and T_2 for W/H = 0.75, 1.5 and 3 from Figure 2-213 (+/+) as summarized below.

W/H	0.75	1.5	3
T_1	1.82	4.95	11.7
T_2	3.20	6.50	12.5

Plot Figure 2A-21 (+/+/+/+) using above values of W/H and T_1 and T_2, and determine T_1 = 4.4 ms and T_2 = 5.9 ms for W/H = 1.33.

c. For P_{so} = 12.6 psi and L/H = 2, determine T_3 and T_4 for W/H = 0.75, 1.5 and 3 and L_w/L = 0.75, 1, 1.5 and 2, from Figures 2-218 (+/+) to 2-221 (+/+), as summarized below:

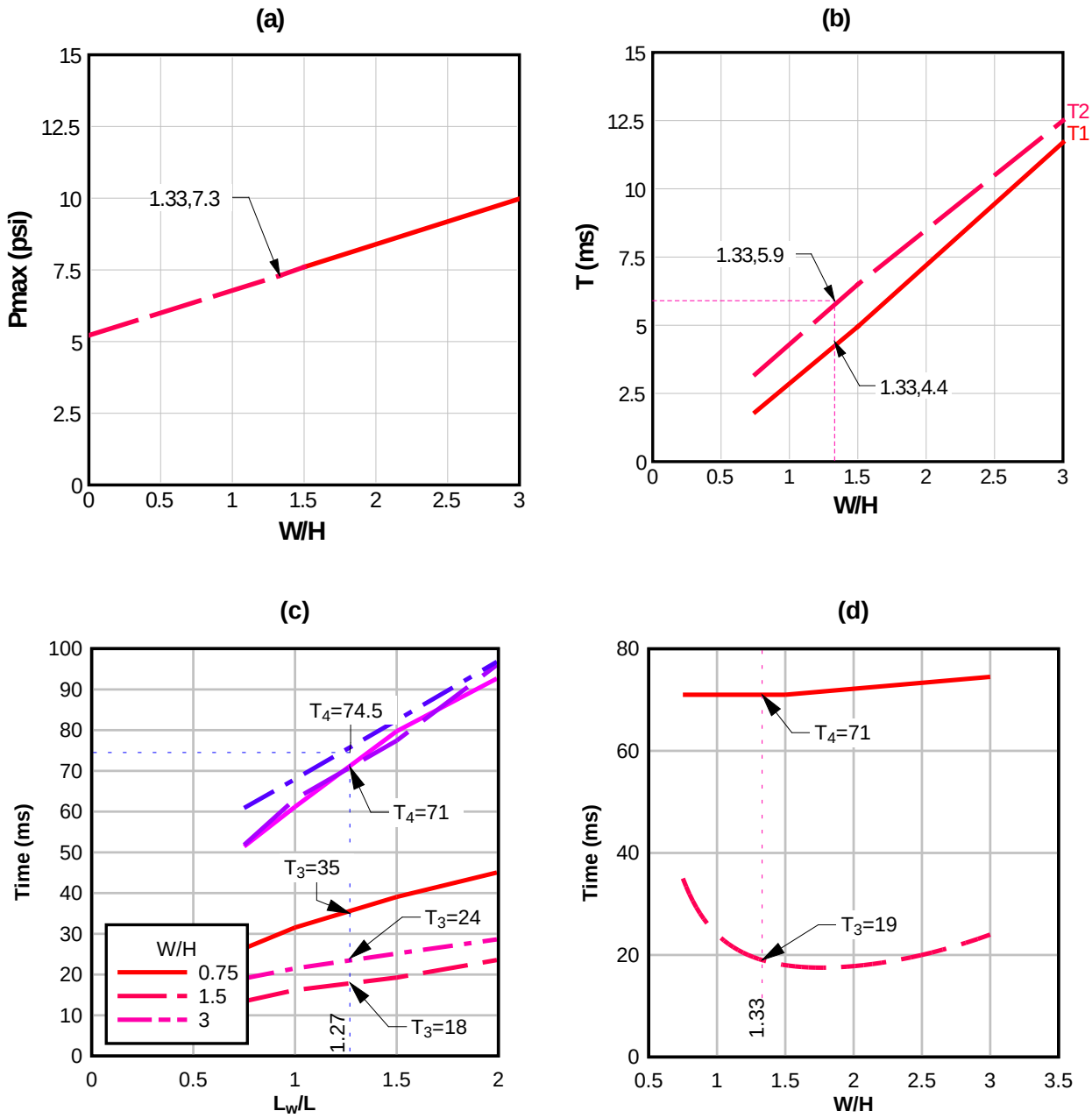
Plot Figure 2A-21 (+/+/+/+) with above values, and interpolate to determine T_3 and T_4, for $L_w/L \approx 1.27$ for W/H = 0.75, 1.5 and 3, as summarized below.

W/H	0.75	1.5	3
T_3	35	18	24
T_4	71	71	74.5

Plot Figure 2A-21 (+/+/+/+) with above values, and determine T_3 = 19 ms and T_4 = 71 ms, for W/H = 1.33.

d. For P_{max} = 7.3 psi, T_1 = 4.4 ms, T_2 = 5.9 ms, T_3 = 19 ms and T_4 = 71 ms plot Figure 2A-23 (+).

Figure 2A-21



Step 5. Back wall idealized interior pressure-time blast load.

a. For L/H = 2, P_{so} = 12.6 psi and A_o/A_w = 1/8, determine P_{RIB}/P_{so} = 0.575 from Figure 2-234 (+).

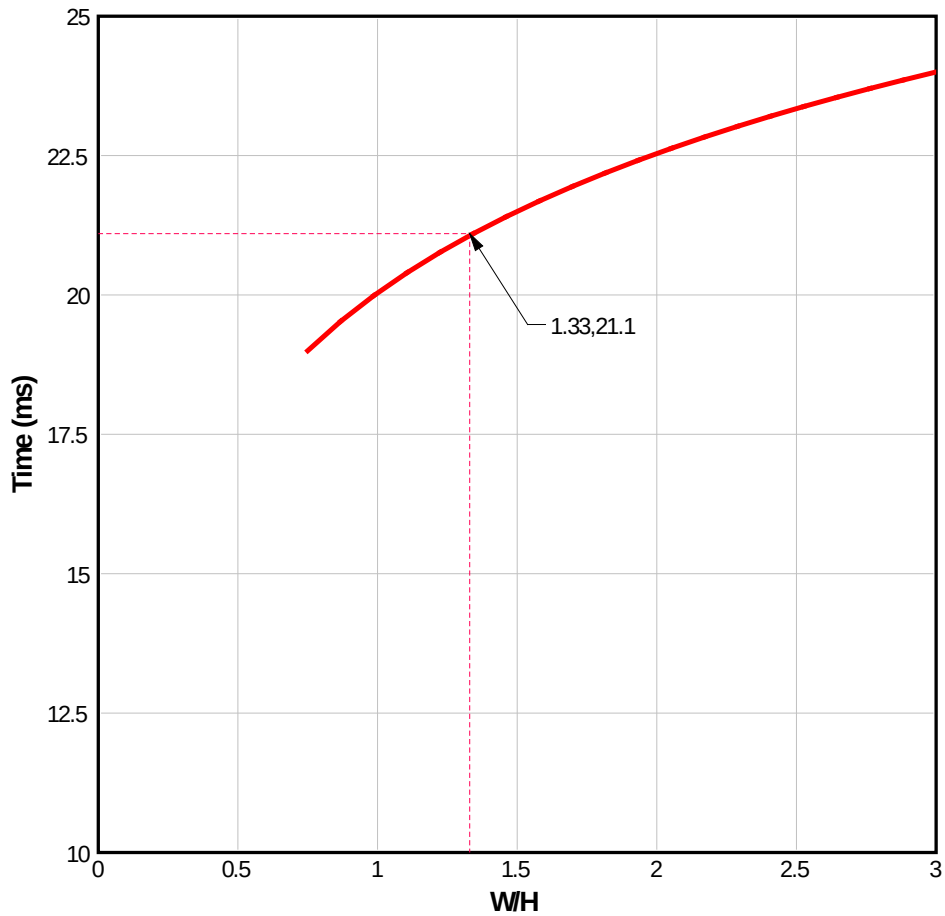
b. $P_{RIB} = (P_{RIB}/P_{so}) \times P_{so} = 0.575 \times 12.6 = 7.5$ psi.

c. For P_{so} = 12.6 psi, L/H = 2, and A_o/A_w = 1/8, determine T_1 for W/H = 0.75, 1.5 and 3 from Figures 2-230 (+/+) and 2-231 (+/+), as is shown below.

W/H	0.75	1.5	3
T_1	19.0	21.5	24.0

Plot Figure 2A-22 (+) using above values, and determine T_1 = 21.1 ms for W/H = 1.33.

Figure 2A-22



d. For P_{so} = 12.6 psi and A_o/A_w = 1/8, determine T_2 - T_1 = 2.35 ms from Figure 2-232 (+/+).

Determine $T_2 = (T_2 - T_1) + T_1$ = 2.35 ms + 21.1 ms = 23.5 ms

e. Plot Figure 2A-23 (+) using P_{RIB} = 7.5 psi, T_1 = 21.1 ms and T_2 = 23.5 ms

Step 6. Roof idealized interior pressure-time blast load

a. Sidewall W/H = 1-1/3 = 4/3

Roof W/H = 1/(4/3) = 3/4

b. Repeat Step 4 with W/H = 3/4

For W/H = 3/4, L/H = 2.0, A_o/A_w = 1/8, L_w/L = 1.272 and P_{so}= 12.6,

P_{max} = 6.2 psi

For W/H = 3/4 and P_{so} = 12.6 psi

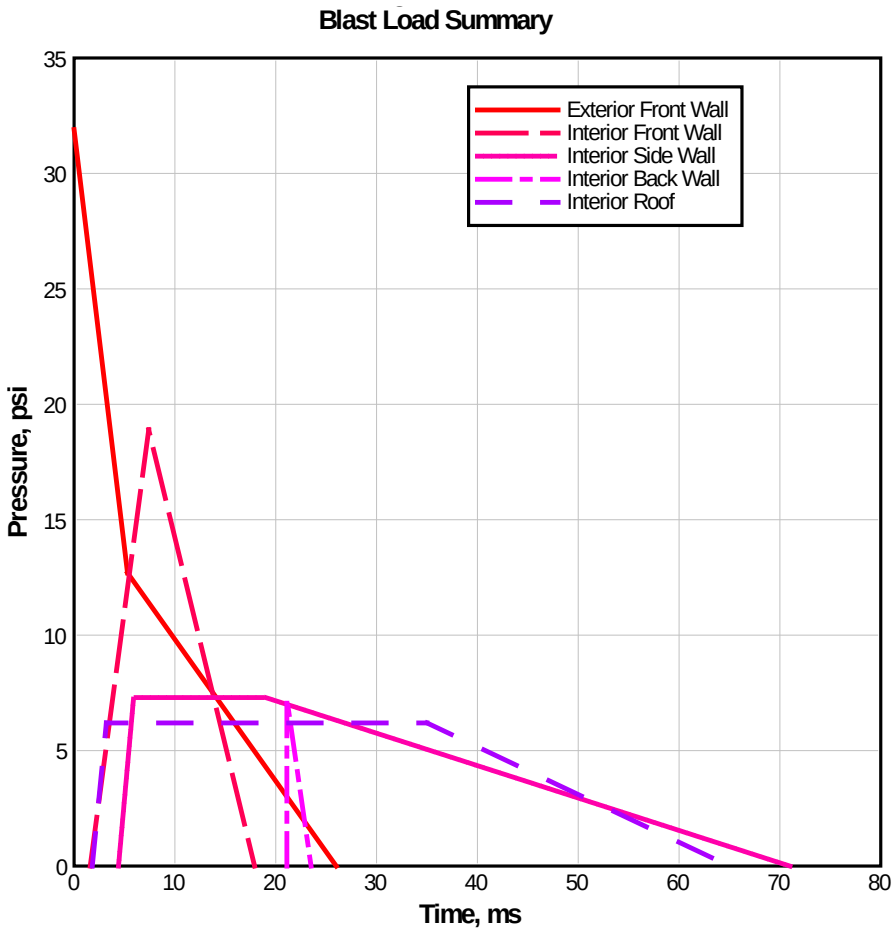
T_1 = 1.82 and T_2 = 3.20 ms

For W/H = 3/4, P_{so} = 12.6 psi and L_w/L = 1.27

T_3 = 35 and T_4 = 65 ms

Plot Figure 2A-23 (+) with above values.

Figure 2A-23


Blast Load Summary
Exterior Front Wall
Interior Front Wall
Interior Side Wall
Interior Back Wall
Interior Roof
Pressure, psi
Time, ms
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60
70
80

PROBLEM 2A-12 INTERIOR PRESSURE BUILDUP IN A STRUCTURE

Problem: **Determine the interior pressure-time curve for a structure with an opening in one of its walls and subjected to an applied blast pressure.**

Procedure:

Step 1. Determine the pressure-time history of the applied blast pressure P acting on the wall surrounding the opening in the structure as presented in Problem 2A-10. Also the area of the opening A_o and the volume of the structure V_o must be known.

Step 2. Divide the duration t_o of the applied pressure into n equal intervals δt, each interval being approximately $t_o/10$ to $t_o/20$, and determine the pressures at the end of each interval.

Step 3. Compute the pressure differential $P\text{-}P_i$ where P_i is the interior pressure. Obtain the leakage pressure coefficient C_L for each $P\text{-}P_i$ from Figure 2-235 (+).

Step 4. Calculate δP_i from

$$\delta P_i = C_L \frac{A_o}{V_o} \delta t \qquad \text{(Equation 2-31)}$$

using the proper values for C_L and δt. Add δP_i to P_i for the interval being considered to obtain the new value of P_i for the next interval.

Step 5. Repeat Steps 3 and 4 for each interval using the proper values of P and P_i. Plot curve of pressure buildup.

Note:

When $P\text{-}P_i$ becomes negative, the value of C_L must be taken as negative also.

EXAMPLE 2A-12 INTERIOR PRESSURE BUILDUP IN A STRUCTURE

Required: Interior pressure-time curve for a structure with an opening in one of its walls and subjected to an applied blast pressure.

Solution:

Step 1. The curve of the applied blast pressure P for the wall in question is shown in Figure 2A-24 (+). (Only the positive phase of the blast wave is considered in this example.)

Area of opening	A_o = 3' x 3' = 9 sq ft
Volume of structure	V_o = 10' x 10' x 10' V_o = 1,000 cu ft

Step 2. t_o = 55 ms

Use n = 10 δt = 5.5 ms

For the first interval, P = 3.5 psi at t = 0

Step 3. P_i = 0 for the first interval

$P - P_i$ = 3.50 - 0 = 3.50 psi

C_L = 8.75 (Figure 2-235 (+))

Step 4. $$\delta P_i = C_L \frac{A_o}{V_o} \delta t$$ (Equation 2-31)

δP_i = 8.75 (9.0 / 1000) (5.5) = 0.433 psi

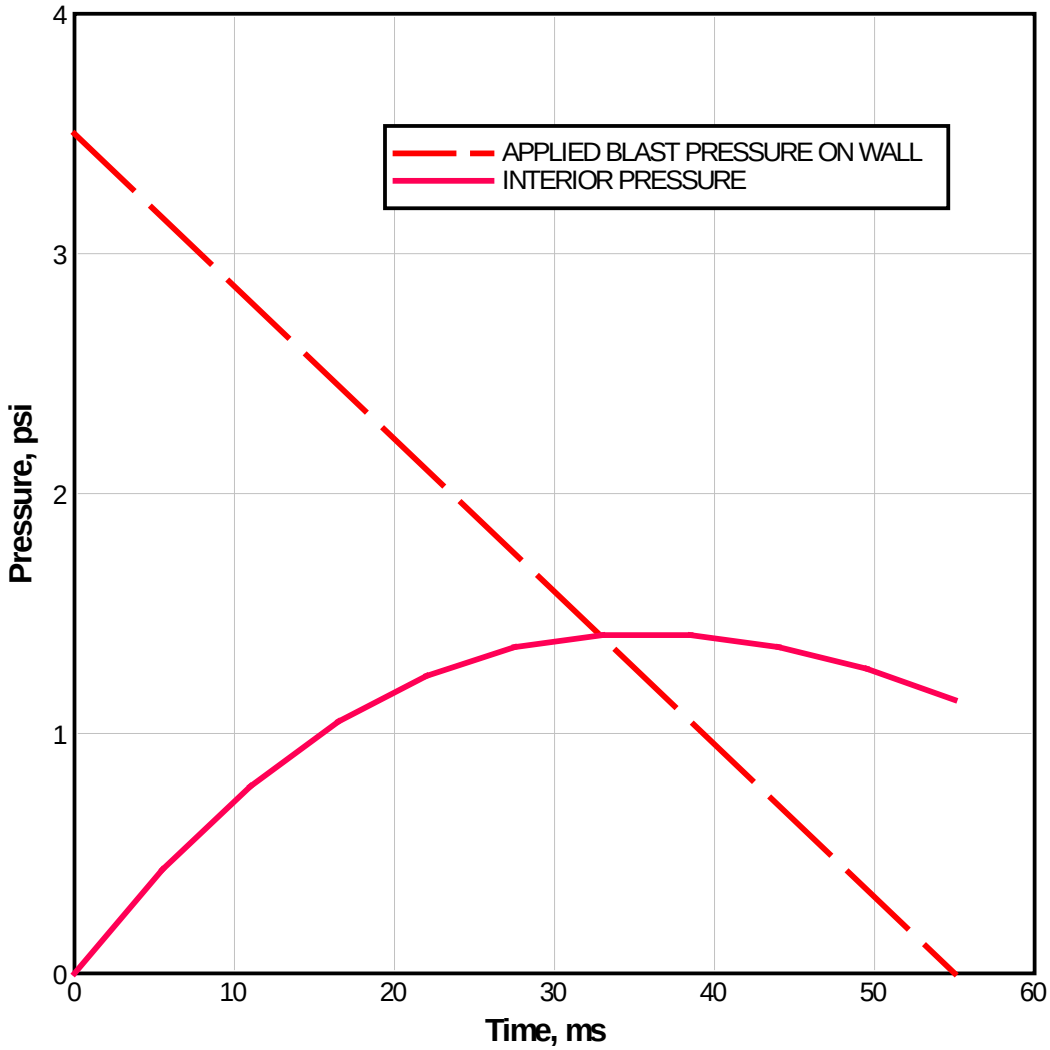
new P_i = 0 + 0.433 = 0.433 psi

Step 5. The remainder of the analysis is presented in tabular form and the pressure buildup within the structure is plotted in Figure 2A-24 (+).

$t^{(1)}$ (ms)	P (psi)	P_i (psi)	P-P_i (psi)	C_L (psi-ft/ms)	δP_i (psi)
0.0	3.50	0.0	3.50	8.75	0.433
5.5	3.15	0.433	2.72	7.00	0.347
11.0	2.80	0.780	2.02	5.45	0.270
16.5	2.45	1.05	1.40	3.78	0.187
22.0	2.10	1.24	0.86	2.32	0.115
27.5	1.75	1.36	0.39	1.05	0.052
33.0	1.40	1.41	-0.01	-0.027	-0.0013
38.5	1.05	1.41	-0.36	-0.972	-0.048
44.0	0.70	1.36	-0.66	-1.78	-0.088
49.5	0.35	1.27	-0.92	-2.48	-0.123
55.0	0.0	1.14	-1.14	-3.50	-0.173
60.5	0.0	0.97	-0.97	-3.00	-0.148
66.0	0.0	0.82	-0.82	-2.50	-0.124
71.5	0.0	0.70	-0.70	-2.25	-0.111
77.0	0.0	0.59	-0.59	-2.00	-0.099
82.5	0.0	0.49	-0.49	-1.80	-0.089
88.0	0.0	0.40	-0.40	-1.60	-0.079
93.5	0.0	0.32	-0.32	-1.45	-0.071
99.0	0.0	0.25	-0.25	-1.30	-0.064
104.5	0.0	0.19	-0.19	-1.15	-0.056
110.0	0.0	0.13	-0.13	-1.0	-0.050
115.5	0.0	0.08	-0.08	-0.85	-0.042
121.0	0.0	0.04	-0.04	-0.05	-0.025
126.5	0.0	0.01	-0.01	-0.2	-0.01
132.0	0.0	0.0	0.0	0.0	0.0

(1) Maximum P_i occurs between t = 27.5 and t = 33.0 ms

Figure 2A-24


APPLIED BLAST PRESSURE ON WALL
INTERIOR PRESSURE
Pressure, psi
Time, ms
0
1
2
3
4
0
10
20
30
40
50
60

PROBLEM 2A-13 PRIMARY FRAGMENTS FROM CASED CYLINDRICAL CHARGES

Problem: **Determine the average fragment weight for a primary fragment ejected from a uniform cylindrical steel casing; the total number of fragments, the design fragment weight and the number of fragments weighing more than the design fragment.**

Procedure:

Step 1. Establish design parameters:

a. type of explosive

b. average casing thickness, t_c

c. average inside diameter of casing, d_i

d. total casing weight, W_c

e. confidence level, C_L

Step 2. Determine the value of the explosive constant B for the given type of explosive from Table 2-6 (+/+). With this value and the values of t_c and d_i from Step 1, calculate the fragment distribution M_A from

$$M_A = Bt_c^{5/6} d_i^{1/3} \left[1 + \left(t_c / d_i\right)\right] \qquad \text{(Equation 2-37)}$$

Step 3. With the value of M_A from Step 2, calculate the average weight of the fragments from

$$\overline{W_f} = 2M_A^{\ 2} \qquad \text{(Equation 2-40)}$$

Step 4. Calculate the total number of fragments using the value of W_c from Step 1d and M_A from Step 2 and Equation 2-37.

$$N_T = 8W_c / M_A^2 \qquad \text{(Equation 2-39)}$$

or: With the values of d_i and t_c from Step 1, enter Figure 2-241 (+) and determine B^2N_T/W_c. From this value, the value of B from Step 2 and W_c from Step 1, find N_T.

Step 5. Find the design fragment weight for the confidence level C_L, given in Step 1, using the value of M_A and

$$W_f = M_A^2 \ln^2(1 - C_L) \text{ for } C_L \leq 0.9999 \qquad \text{(Equation 2-42)}$$

or Equation 2-43 if $C_L > 0.9999$

Step 6. Using the value of W_c from Step 1, M_A from Step 2 and W_f from Step 5, determine the number of fragments which weigh more than the design fragment from

$$N_f = \frac{8W_c e^{-\left[(W_f)^{1/2}/M_A\right]}}{M_A^{\ 2}} \qquad \text{(Equation 2-36)}$$

or: Calculate the number of fragments which weigh more than the design fragment using the confidence level of Step 1, the total number of fragments from Step 4 and Equation 2-244.

EXAMPLE 2A-13 PRIMARY FRAGMENTS FROM CASED CYLINDRICAL CHARGES

Required: The average fragment weight, the total number of fragments, the design fragment weight and the number of fragments weighing more than the design fragment.

Solution:

Step 1. Given:

a. type of explosive: Comp B
b. average casing thickness: t_c = 0.50 inch
c. average inside diameter of casing: d_i = 12.0 inches
d. total casing weight: W_c = 65.0 lbs
e. confidence level: C_L = 0.95

Step 2. For Comp B, B = 0.22 (Table 2-7 (+))

$M_A = Bt_c^{5/6}d_i^{1/3}(1 + t_c/d_i)$ (Equation 2-37)

$= 0.22\ (0.5)^{5/6}\ (12)^{1/3}\ (1 + 0.5/12) = 0.294$

Step 3. Average weight of fragments.

$\overline{W_f} = 2M_A^2 = 2 \text{ X } (0.294)^2 = 0.17$ oz (Equation 2-40)

Step 4. Total number of fragments.

$N_T = 8W_c/M_A^2 = 8 \text{ X } 65/0.294^2 = 6016$ fragments (Equation 2-39)

or: $\dfrac{B^2N_T}{W_c} = 0.28$ (Figure 2-37 (+/+/+))

$N_T = 0.28 \text{ X } (65 \text{ X } 16)/0.22^2 = 6016$ fragments

Step 5. Design fragment weight.

$W_f = M_A^2 \ln^2(1 - C_L) = 0.294^2 \ln^2(1 - 0.95) = 0.78$ oz (Equation 2-42)

Step 6. Number of fragments weighing more than W_f = 0.78 oz

$$N_f = \frac{8W_c e^{-\left[(W_f)^{1/2}/M_A\right]}}{M_A{}^2} = \frac{(8 \times 65)e^{-(0.78)^{1/2}/0.294}}{(0.294)^2}$$

= 298 fragments (Equation 2-36)

or: $C_L = 1 - N_f/N_T$ (Equation 2-44)

$N_f = N_T\ (1 - C_L) = 6016\ (1 - 0.95) = 301$ fragments

PROBLEM 2A-14 PRIMARY FRAGMENT VELOCITY

Problem: **Determine the initial velocity of a primary fragment and its striking velocity.**

Procedure:

Step 1. Establish design parameters.

a. shape of charge

b. dimensions of charge

c. type and density of explosive

d. type and density of casing

e. distance from center of charge to impact location

f. weight of fragment

Step 2. Calculate the total weight of the explosive W and increase it 20%. Find the weight of the casing W_c. Also calculate the ratio of the explosive weight to the casing weight W/W_c.

Step 3. Determine the Gurney Energy Constant $(2E')^{1/2}$ for the explosive charge from Table 2-5 (+). With this value and the value of W/W_c from Step 2, calculate the initial v_o of the primary fragments from the equation chosen from Table 2-6 (+/+).

or: Calculate the casing to charge weight ratio W_c/W. With W_c/W, find the initial velocity from Figure 2-237 (+) for proper shape.

Step 4. For the distance traveled by the fragment R_f, calculate the striking velocity v_s using the initial velocity from Step 3, the weight of the fragment from Step 1g and

$$v_s = v_o e^{-.004 R_f / W_f^{1/3}} \qquad \text{(Equation 2-48)}$$

or: With the fragment weight W_f and striking distance R_f from Step 1, enter Figure 2-243 (+) and find the ratio of the striking velocity to initial velocity. Multiply the ratio by the initial velocity v_o from Step 3 to find the striking velocity v_s.

EXAMPLE 2A-14 PRIMARY FRAGMENT VELOCITY

Required: The initial velocity and striking velocity of a primary fragment.

Solution:

Step 1. Given:

a. spherical charge

b. inner diameter of charge: d_i = 6 inches

average casing thickness: t_c = 0.25 inches

c. type of explosive TNT

density of explosive = 0.0558 lb/in^3

d. mild steel casing

density of casing = 0.283 lb/in^3

e. striking distance R_f = 35 ft

f. weight of fragment, W_f = 2 oz

Step 2.

a. weight of the explosive

$W = 4/3\ \pi\ (6/2)^3 \times 0.0558 = 6.31$ lbs

b. Increase weight of explosive 20 percent

$W = 1.20 \times 6.31 = 7.57$ lb

c. Weight of casing

$W_c = 4/3\ \pi\ (3.25^3 - 3^3) \times 0.283 = 8.69$ lb

d. Explosive weight to casing weight ratio.

$W/W_c = 7.57/8.69 = 0.871$

Step 3. For TNT, $(2E')^{1/2} = 8000$ (Table 2-5 (+))

Initial velocity from Table 2-6 (+/+)

$$v_o = (2E')^{1/2}\left[\frac{W/W_c}{1+(3W/5W_c)}\right]^{1/2}$$

$$v_o = (8000)\left[\frac{0.87}{1+0.87(3/5)}\right]^{1/2} = 6050\,\text{ft/sec}$$

or: $W_c/W = 8.69/7.57 = 1.15$

from Figure 2-237 (+)

$v_o/(2E')^{1/2} = 0.76$

$v_o = 0.76 \times 8000 = 6080$ ft/sec

Step 4. Striking velocity

$$v_s = v_o e^{-0.004R_f/W_f^{1/3}} = 6080e^{-.0.004[35/(2^{1/3})]} \qquad \text{(Equation 2-48)}$$

$v_s = 5440$ ft/sec

or: from Figure 2-243 (+) for $W_f = 2$ oz and $R_f = 35$ ft

$v_s/v_o = 0.895$

$v_s = 0.895 \times 6080 = 5440$ ft/sec

PROBLEM 2A-15 UNCONSTRAINED SECONDARY FRAGMENTS "CLOSE" TO A CHARGE

Problem: **Determine the velocity of an unconstrained object close to an explosive charge and its maximum range.**

Procedure:

Step 1. Establish design parameters

a. weight W and shape of TNT equivalent explosive

b. radius of explosive R_e

c. shape, dimensions and weight of target

d. distance from the center of the explosive charge to the surface of the target, R

e. orientation of target with respect to the explosive charge

f. mass density of air ρ_o

Step 2. Calculate the ratio of standoff distance to radius of the explosive R/R_e using the values from Step 1.

Step 3. From Figure 2-249 (+), determine target shape factor, $ß$.

Step 4.

a. If R/R_e is less than or equal to 10 for cylindrical charges, or less than equal to 5.0 for spherical charges, determine the specific acquired impulse either from Figure 2-250 (+) or Equations 2-60, or 2-61.

b. If $10 < R/R_e \leq 20$ for a cylindrical charge, or $5 < R/R_e \leq 20$ for a spherical charge, calculate the scaled standoff distance $Z_A = R/W^{1/3}$. With that value of Z_A, obtain the normal reflected impulse from Figure 2-7 (+). The normal reflected impulse is then used as the specific acquired impulse.

Step 5. Calculate the mean presented area A of the target and the mass M using the values of Step 1.

Step 6. With the area and mass from Step 4, the target shape factor $ß$ from Step 2 and the impulse from Step 3, calculate the velocity from

$$v_o = \frac{1000 A \beta i}{12M} \qquad \text{(Equation 2-59)}$$

Step 7. Determine the drag coefficient C_D from Table 2-8 (+). Using that value of C_D, the area and mass of the target from Step 5, the velocity from Step 6 and the mass density of air from Step 1f,

evaluate the term: $12\ \rho_o C_D A_D v_o^2 / Mg$.

Step 8. With the term calculated in Step 7, enter Figure 2-252 (+) and read the value of $12\ \rho_o C_D A_D R / M$ from which the range R is calculated.

EXAMPLE 2A-15 UNCONSTRAINED SECONDARY FRAGMENTS "CLOSE" TO A CHARGE

Required: The velocity and maximum range of a steel tool holder resting on a lathe when a charge being held by the lathe explodes.

Solution:

Step 1. Given:

a. spherical charge of TNT

W = 15 lbs

b. radius of explosive: R_e = 0.33 ft

c. cylindrical target; length = 8.0 in

R_t = 1.0 in = 0.083 ft

W_t = 7.13 lb

d. standoff distance: R = 1.0 ft

e. tool holder is resting so that its longitudinal axis is perpendicular to the radial line from the charge

f. mass density of air: ρ_o = 0.115 lb - ms^2/in^4

Step 2. Ratio of standoff distance to radius of explosive:

R/R_e = 1.0/0.33 = 3.03

Step 3. Target shape factor.

$ß = \pi/4$ from Figure 2-249 (+)

Step 4. Determine specific acquired impulse

a. $$\frac{i}{\beta R_{eff}}\left[\frac{R_e}{R_t}\right]^{0.158} = 8000\frac{\text{psi}-\text{ms}}{\text{ft}}$$ (Figure 2-250 (+))

b. $R_{eff} = R_e$ = 0.33 ft (Equation 2-61)

c. $i = \pi/4$ (0.33 ft) (0.083/0.33)$^{0.158}$ X 8000 psi-ms/ft

i = 1667 psi-ms

Step 5. Calculate area and mass of target.

a. Mean presented area

A = 2.0 in X 8.0 in = 16 in^2

b. Mass

$$M = \frac{W_t}{g} = \frac{7.13\text{lb}}{32.2 \times 12 \times 10^{-6}\text{in/ms}^2} = 18{,}450\frac{\text{lb} - \text{ms}^2}{\text{in}}$$

Step 6. Find the velocity.

$$v_o = \frac{1000A\beta i}{12M} = \frac{1000 \times 16 \times (\pi / 4) \times 1667}{12 \times 18450} \qquad \text{(Equation 2-59)}$$

v_o = 95 ft/sec

Step 7. Evaluate the term 12 ρ_o $C_D A_D v_o^2/Mg$.

a. C_D = 1.2 (Table 2-8 (+))

b. $$\frac{12\rho_o C_D A_D V_o^{\ 2}}{Mg} = \frac{12 \times 0.115 \times 1.2 \times 16 \times (95)^2}{18450 \times 32.2} = 0.40$$

Step 8. Calculate the range.

a. $$\frac{12\rho_o C_D A_D R}{M} = 0.33 \qquad \text{(Figure 2-252 (+))}$$

b. R = $0.33M/(12\rho_o C_D A_D)$

= 0.33 (18450)/[12 (0.115) 1.2 (16)] = 230 ft

PROBLEM: 2A-16 UNCONSTRAINED SECONDARY FRAGMENTS "FAR" FROM A CHARGE

Problem: **Determine the velocity of an unconstrained object "far" from an explosive charge.**

Procedure:

Step 1. Establish design parameters:

a. weight W of TNT equivalent explosive

b. shape, dimensions and weight of target

c. distance from the center of explosive charge to surface of the target

d. orientation and location of target with respect to the explosive charge

e. velocity of sound in air, a_o

f. atmospheric pressure, p_o

Step 2. Calculate the scaled standoff distance from:

$$Z_A = R_A / W^{1/3}$$

From Figure 2-7 (+) and the scaled distance find the peak incident overpressure and the incident specific impulse.

Step 3. Determine the drag coefficient C_D from Table 2-8 (+) based on the shape and orientation of target (Step 1).

Step 4. Calculate the mass of the target. Determine the distance from the front of the target to the location of its largest cross-sectional area, X. Also, determine the minimum transverse distance of the mean presented area, H, and the presented area.

Step 5. Determine the constant K, which is equal to 4 if the object is on the ground or reflecting surface. If the target is in the air, K is equal to 2.

Step 6. With the peak incident overpressure P_{so} from Step 2 and the atmospheric pressure p_o from Step 1f, find P_{so}/p_o.

Step 7. Evaluate the term $12C_D i_s a_o/10^3[P_{so}(KH + X)]$ using i_s and P_{so} from Step 2, C_D from Step 3, a_o from Step 1e, K from Step 5 and H and X from Step 4.

Step 8. With two terms calculated in Steps 6 and 7 enter Figure 2-248 (+) and read $144v_o Ma_o/[10^6 P_o A(KH + X)]$ from which the velocity is calculated.

EXAMPLE 2A-16 UNCONSTRAINED SECONDARY FRAGMENTS "FAR" FROM CHARGE

Required: The initial velocity of a steel tool holder resting on a nearby table, when a charge explodes.

Solution:

Step 1. Given:

a. weight of explosive: W = 15 lbs of TNT

b. cylindrical target: length = 8.0 in

R_t = 1.0 in

W_t = 7.13 lb

c. standoff distance: R = 10 ft

d. tool holder is resting on a table so that its longitudinal axis is perpendicular to the radial line from the charge

e. velocity of sound in air: a_o = 1100 ft/sec

f. atmospheric pressure: p_o = 14.7 psi

Step 2. Find the peak incident overpressure and the incident specific impulse.

a. Scaled distance

$Z_A = R/W^{1/3} = 10/(15)^{1/3} = 4.05$ ft/lb$^{1/3}$

b. Peak incident overpressure.

P_{so} = 46 psi (Figure 2-7 (+))

c. Incident specific impulse.

$i_s/W^{1/3}$ = 12 psi-ms/lb$^{1/3}$ (Figure 2-7 (+))

$i_s = 12\ (15)^{1/3} = 29.6$ psi-ms

Step 3. Drag coefficient.

C_D = 1.2 (from Table 2-8 (+) for cylinder loaded perpendicular to axis.)

Step 4.

a. Mass of target.

$$M = \frac{W_t}{g} = \frac{7.13\ lb}{32.2 \times 12 \times 10^{-6}\ in/ms^2} = 18{,}450 \frac{lb\text{ - }ms^2}{in}$$

b. Location of largest cross-section.

X = 1 in (radius of object in this case - see Figure 2A-21 (+/+/+/+))

c. Transverse distance of presented area.

H = 2.0 in (diameter of object in this case - see Figure 2A-25 (+))

d. Mean presented area.

A = 2 x 8 = 16 in^2

Step 5. Reflection constant.

Target is resting on table which is a reflecting surface so:

K = 4

Step 6. Evaluate P_{so}/p_o

P_{so}/p_o = 46/14.7 = 3.13

Step 7. Evaluate $12C_D i_s a_o/[10^3 P_{so}(KH + X)]$

$$\frac{12C_D i_s a_o}{10^3 P_{so}(KH + X)} = \frac{12 \times 1.2 \times 29.6 \times 1100}{10^3 \times 46 \times (2 \times 4 + 1)} = 1.13$$

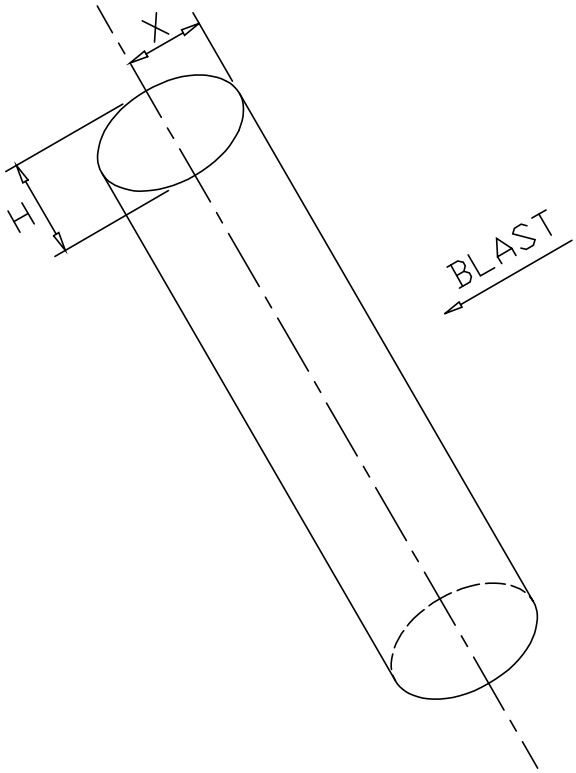
Step 8. Calculate the velocity.

$$\frac{144 v_o M a_o}{10^6 p_o A(KH + X)} = 7.5$$ (Figure 2-248 (+))

$$v_o = \frac{7.5 p_o A(KH + X) 10^6}{144 M a_o} = \frac{10^6 \times 7.5 \times 14.7 \times 16 \times (2 \times 4 + 1)}{144 \times 18450 \times 1100}$$

v_o = 5.43 ft/sec

Figure 2A-25



PROBLEM 2A-17 CONSTRAINED SECONDARY FRAGMENTS

Problem: **Determine the velocity of a constrained object close to an exploding charge.**

Procedure:

Step 1. Establish design parameters:

a. fragment material.

b. dimensions of object.

c. boundary condition, cantilever or fixed-fixed.

d. specific impulse imparted to object.

Step 2. Determine the fragment toughness T from Table 2-9 (+) and the fragment mass density ρ_f.

Step 3. Calculate the loaded area of the object.

Step 4. Evaluate the term $ib\ (2L/b)^{0.3}/[A(\rho_f\ T)^{0.5}]$,using the specific impulse and object dimensions from Step 1, the fragment density and toughness from Step 2 and the loaded area from Step 3. With this term, enter Figure 2-251 (+) and read the value of $12V/1000\ (\rho_f\ /T)^{0.5}$ from which the velocity is calculated.

or: Using the specific impulse and object dimensions from Step 1, the fragment density and toughness from Step 2, and the loaded area from Step 3. Calculate the velocity of the object from Equation 2-66.

EXAMPLE 2A-17 CONSTRAINED SECONDARY FRAGMENTS

Required: The velocity of a cylindrical tool holder after it breaks free of its moorings.

Solution:

Step 1. Given:

a. fragment material; A36 steel

b. dimensions of object: b = 2.0 inches, L = 8.0 inches

c. boundary conditions; cantilever

d. specific impulse: i = 1667 psi-ms (see Step 4 of Example 2A-15).

Step 2.

a. Fragment toughness.

T = 12,000 in-lb/in^3 (Table 2-9 (+))

b. Mass density of steel.

$$\rho_f = \frac{490\text{lb/ft}^3\left(\text{ft}^3/1728\text{in}^3\right)}{32.2\text{ft/s}^2\left(12\text{in/ft}\right)\left(\text{s}^2/10^6\text{ms}^2\right)} = 734\frac{\text{lb}-\text{ms}^2}{\text{in}^4}$$

Step 3. Loaded area.

$A = \pi r^2 = \pi\,(1.0)^2 = 3.14\text{ in}^2$

Step 4. Calculate the velocity.

$$\frac{ib}{A\left(\rho_f T\right)^{0.5}}\left[\frac{2L}{b}\right]^{0.3} = \frac{1667\times 2.0}{3.14\times\left(734\times 12{,}000\right)^{0.5}}\left[\frac{2\times 8}{2}\right]^{0.3} = 0.668$$

from Figure 2-251 (+)

$12/1000\ [\rho_f/T]^{1/2}\ V = 0.025$

so

$$V = \frac{1000}{12}\left[\frac{T}{\rho_f}\right]^{1/2} 0.025 = \frac{1000}{12}\left[\frac{12{,}000}{734}\right]^{1/2} 0.025 = 8.4\text{fps}$$

or from Equation 2-66

$$V = \frac{1000}{12}\left[\frac{T}{\rho_f}\right]^{1/2}\left[-.2369 + 0.3931\left[\frac{ib}{(\rho_f T)^{1/2} A}\right]\left[\frac{2L}{b}\right]^{0.3}\right]$$

$$= \frac{1000}{12}\left[\frac{12{,}000}{734}\right]^{1/2}\left(-.2369 + 0.3931 \times 0.668\right)$$

$$= 8.6\text{fps}$$

PROBLEM 2A-18 GROUND SHOCK LOAD

Problem: **Determine the air blast and direct induced ground shock parameters.**

Procedure:

Air Blast-Induced Ground Shock

Step 1. Determine the charge weight, ground distance R, height of burst H_c, if any, and structure dimensions.

Step 2. Apply a 20% safety factor to the charge weight.

Step 3. Calculate the scaled distance Z.

Read: From Figure 2-15 (+)

a. Peak positive incident pressure P_{so}.

b. Scaled unit positive incident impulse $i_s/W^{1/3}$. Multiply scaled value by $W^{1/3}$ to obtain absolute value.

c. Shock front velocity U.

Step 4. Determine the maximum vertical ground motions.

a. Calculate maximum vertical velocity.

$$V_V = \frac{P_{so}}{\rho C_p} \qquad \text{(Equation 2-74)}$$

where:

ρ = Mass density of soil (Table 2-10 (+))

C_p = Compression wave seismic velocity in the soil (Table 2-11 (+))

b. Calculate maximum vertical displacement

$$D_V = \frac{i_s}{1{,}000\rho C_p} \qquad \text{(Equation 2-74)}$$

c. Calculate maximum vertical acceleration of the ground surface.

$$A_V = \frac{100P_{so}}{\rho C_p g} \qquad \text{(Equation 2-76)}$$

where:

g = Gravitational constant equal to 32.2 ft/sec^2

Step 5. Determine the maximum horizontal ground motions parameters.

a. Check $C_p/(12000\ U) > .707$

b. Calculate maximum horizontal velocity.

$$V_H = V_V \tan\left[\sin^{-1}\left(C_p/(12{,}000\ U)\right)\right] \qquad \text{(Equation 2-77)}$$

c. Calculate maximum horizontal displacement.

$$D_H = D_V \tan\left[\sin^{-1}\left(C_p/(12{,}000\ U)\right)\right] \qquad \text{(Equation 2-78)}$$

d. Calculate maximum horizontal acceleration.

$$A_H = A_V \tan\left[\sin^{-1}\left(C_p/(12{,}000\ U)\right)\right] \qquad \text{(Equation 2-79)}$$

Step 6. Determine arrival time t_A and duration t_o:

a. Read from Figure 2-15 (+).

$t_A/W^{1/3}$ scaled time of arrival of blast wave and,

$t_o/W^{1/3}$ scaled duration of positive phase.

b. Multiply scaled value by $W^{1/3}$ to obtain absolute value.

Direct-Induced Ground Shock

Step 7. Determine the maximum vertical ground motions.

a. Calculate maximum vertical displacement.

$$D_V = \frac{0.025 R_G^{1/3} W^{1/3}}{Z_G^{1/3}} \qquad \text{(Equation 2-80, rock media)}$$

or

$$D_V = \frac{0.017 R_G^{1/3} W^{1/3}}{Z_G^{2.3}} \qquad \text{(Equation 2-83, dry or saturated soil)}$$

b. Calculate the maximum vertical velocity.

$$V_V = 150/Z_G^{1.5} \qquad \text{(Equation 2-85)}$$

c. Calculate the maximum vertical acceleration.

$$A_V = 10{,}000/W^{1/3} Z_G^2 \qquad \text{(Equation 2-87)}$$

Step 8. Determine the maximum horizontal ground motion parameters.

a. Calculate the maximum horizontal displacement.

$D_H = 0.5\ D_V$ (Equation 2-82, rock media)

or

$D_H = D_V$ (Equation 2-84, dry or saturated soil)

b. Calculate the maximum horizontal velocity.

$V_H = V_V$ (Equation 2-86, all ground media)

c. Calculate the maximum horizontal acceleration.

$A_H = 0.5\ A_V$ (Equation 2-88, dry soil)

$A_H = A_V$ (Equation 2-89, wet soil or rock media)

Step 9. Determine arrival time t_{AG}:

$t_{AG} = 12000\ R_G/C_p$ (Equation 2-92)

EXAMPLE 2A-18 GROUND SHOCK LOADS

Required: Maximum acceleration, velocity, and displacement at a point 155 ft away from a surface burst of 5,000 lbs. Also required are: times of arrival and duration of air-blast induced ground shock.

Solution:

Air blast-induced ground shock.

Step 1. Given: Charge weight = 5,000 lbs, R = 155 ft, H_c = 12 ft

Step 2. W = 1.2 (5,000) = 6,000 lbs

Step 3. Calculate the scaled distance Z.

$$Z = \frac{R}{W^{1/3}} = \frac{155}{(6{,}000)^{1/3}} = 8.53\ ft/lb^{1/3}$$

Read from Figure 2-15 (+).

a. P_{so} = 13 psi

b. $\frac{i_s}{W^{1/3}} = 9\ psi \cdot ms/lb^{1/3}$

$i_s = 9 \times W^{1/3} = 9 \times (6{,}000)^{1/3} = 163.54$ psi-ms

c. U = 1.5 ft/ms

Step 4. Determine the maximum vertical ground motion.

a. $$V_V = \frac{P_{so}}{\rho C_p}$$ (Equation 2-74)

$$V_V = \frac{13}{1.65 \times 10^{-4} \times 70{,}000} = 1.125 \text{ in/sec}$$

b. $$D_V = \frac{i_s}{1{,}000 \rho C_p}$$ (Equation 2-75)

$$D_V = \frac{163.5}{1{,}000\left(1.65 \times 10^{-4}\right)70{,}000} = 0.0142 \text{ in}$$

c. $$A_V = \frac{100P_{so}}{\rho C_p g}$$ (Equation 2-76)

$$A_V = \frac{100 \times 12.8}{\left(1.65 \times 10^{-4}\right) 70{,}000 \times 32.2} = 3.44g$$

Step 5. Determine the maximum horizontal ground motion.

a. Check $C_p/(12000\ U) > 0.707$

70,000/(12,000 x 1.5) = 3.89 > 0.707

b. $V_H = V_V = 1.125$ in/sec

c. $D_H = D_V = 0.0142$ in

d. $A_H = A_V = 3.44$ g

Step 6. Arrival time t_A

a. Read from Figure 2-15 (+).

$t_A/W^{1/3} = 3.35$ ms/lb$^{1/3}$

$t_o/W^{1/3} = 2.35$ ms/lb$^{1/3}$

b. $t_A = 3.35 \times W^{1/3} = 3.35\ (6{,}000)^{1/3}$

$t_A = 60.90$ ms

$t_o = 2.35 \times W^{1/3} = 2.35 \times (6{,}000)^{1/3}$

$t_o = 42.70$ ms

Direct-induced ground shock.

Step 7. Maximum vertical ground motions.

a. $$D_V = \frac{0.17 R_G^{1/3} W^{1/3}}{Z_G^{2.3}}$$ (Equation 2-83)

$$= \frac{0.17(155)^{1/3}(6{,}000)^{1/3}}{(8.53)^{2.3}} = 0.1198 \text{ in}$$

b. $V_V = 150/Z_G^{1.5}$ (Equation 2-85)

$V_V = 150 / 8.53^{1.5} = 6.020$ in/sec

c. $A_V = 10{,}000 / W^{1/3} Z_G^2$ (Equation 2-87)

$A_V = 10{,}000 / [(6{,}000)^{1/3} (8.53)^2] = 7.56\ g$

Step 8. Horizontal ground motions.

a. $D_H = D_V$ (Equation 2-84)

$D_H = 0.1198$ in

b. $V_H = V_V$ (Equation 2-86)

$V_H = 6.020$ in/sec

c. $A_H = 0.5\ A_V$ (Equation 2-88)

$A_H = 0.5\ (7.56)$

$A_H = 3.78$ g

Step 9. Arrival time t_{AG}

$t_{AG} = 12{,}000\ R_G / C_p = (12{,}000 \times 155) / 70{,}000$ (Equation 2-92)

$t_{AG} = 26.6$ ms

PROBLEM 2A-19 STRUCTURE MOTION DUE TO AIR SHOCK

Problem: **Determine the maximum horizontal acceleration, displacement and velocity of an above ground structure subjected to air shock.**

Procedure:

Step 1. Determine external loadings acting on the roof, front and rear walls according to the procedure outlined in Problem 2A-10.

Step 2. Construct the horizontal force-time load curve by combining the front and rear wall loadings from Step 1 applied over the area of front and rear walls. Use times of arrival to phase these two loads.

Step 3. Calculate the dead weight and mass of the structure.

Step 4. Construct the downward force-time curve by adding the weight of the structure and total roof load. The roof load is the pressure time loading from Step 1 applied over the total area of the roof.

Step 5. Determine the coefficient of friction between soil and the structure from Table 2-12 (+).

Step 6. Determine maximum horizontal acceleration, displacement and velocity using the acceleration impulse extrapolation method outlined in Chapter 3, Section 3-19.2.1.2 of this manual. The resisting force at each time interval is equal to the value of downward force curve of Step 4 multiplied by the coefficient of friction determined in Step 5. The resisting force is assumed to be effective when the total horizontal movement is equal to or larger than 1/4 inch as mentioned in Section 2-22.2.

EXAMPLE 2A-19 STRUCTURE MOTION DUE TO AIR SHOCK

Required: Maximum horizontal acceleration, velocity and displacement of the square structure shown in Figure 2A-9 (+) from Problem 2A-10 for a surface burst of 5,000 lbs at a distance from the front wall of 155 ft. Assume a coarse and compact soil. Roof, floor slab and side walls are 1 foot thick reinforced concrete slabs and assume a 50 psf of internal dead load for the structure.

Step 1. External loadings on the structure are determined according to the procedure in Example 2A-10. See Figure 2A-10 (+), Figure 2A-12 (+) and Figure 2A-13 (+). The arrival time (t_A) for these loads are tabulated in Step 3d of Example 2A-10.

t_{Af} (front wall) = 60.9 ms

t_{Ab} (rear wall) = 83.6 ms

Step 2.

a. Calculate area of front and rear walls.

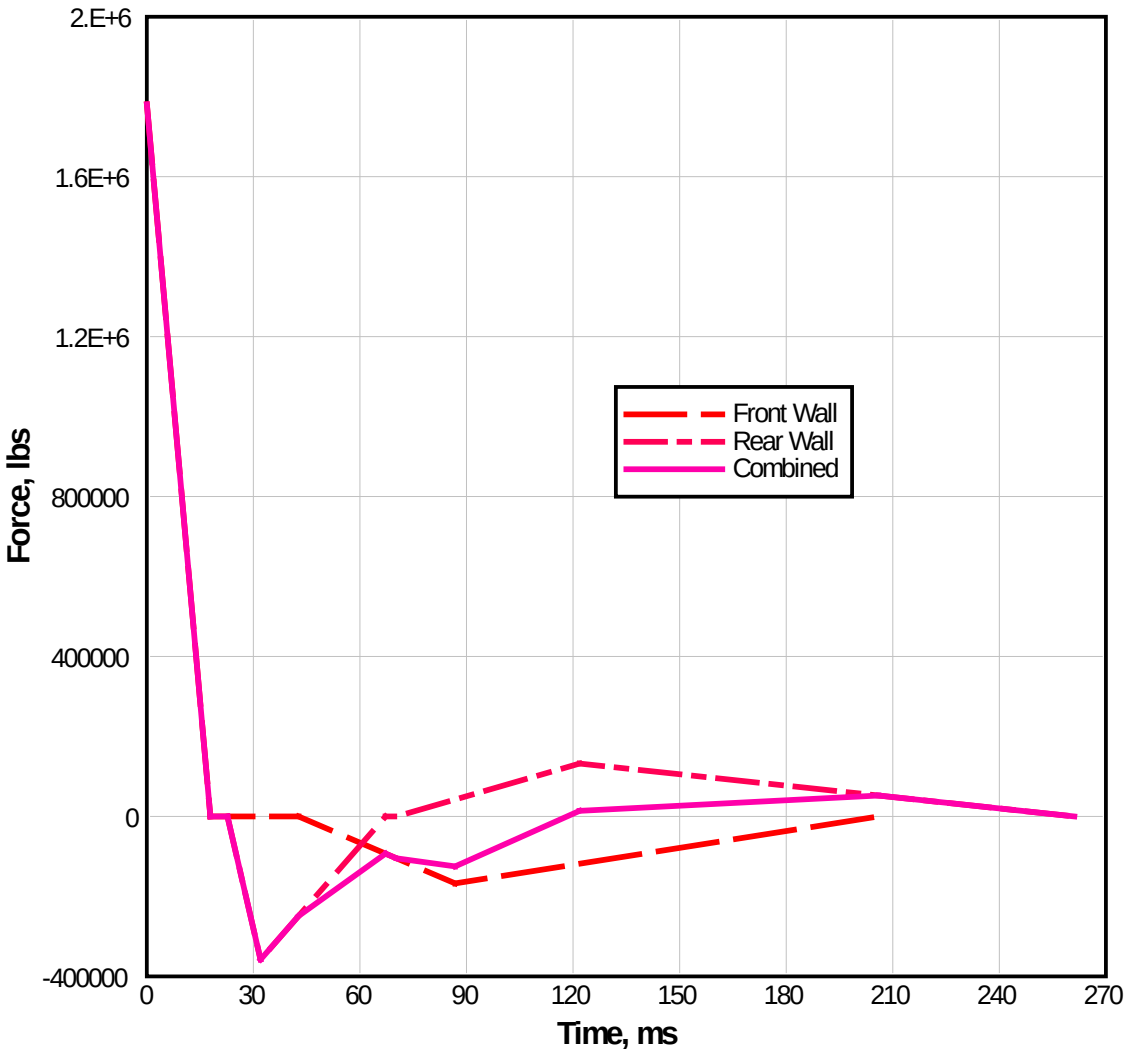
Area (front and rear) = 30 x 12 x $(12)^2$ = 51840 in^2

b. Calculate the time difference between the rear and front walls from Step 1.

$\delta t = t_{Ab} - t_{Af}$ = 83.6 - 60.9 = 22.7 ms

c. Construct the horizontal force-time load curve by multiplying the values of the front and rear wall curves from Step 1 by the area from Step 2a. Rear wall load starts at time equal to δt = 22.7 from Step 2b. See Figure 2A-26 (+).

Figure 2A-26



Step 3.

a. Calculate dead weight of structure W_d. Assume concrete weight is 150 psf.

W_d = 150 [4 (30 - 1) (12-1) + 2 $(30)^2$] + 50 $(30\text{-}2)^2$ = 500,600 lbs

b. Calculate total mass.

$$m = \frac{W_d}{g} = \frac{500{,}600(1000)^2}{32.2 \times 12} = 1295.55 \times 10^6 \frac{\text{lb} - \text{ms}^2}{\text{in}}$$

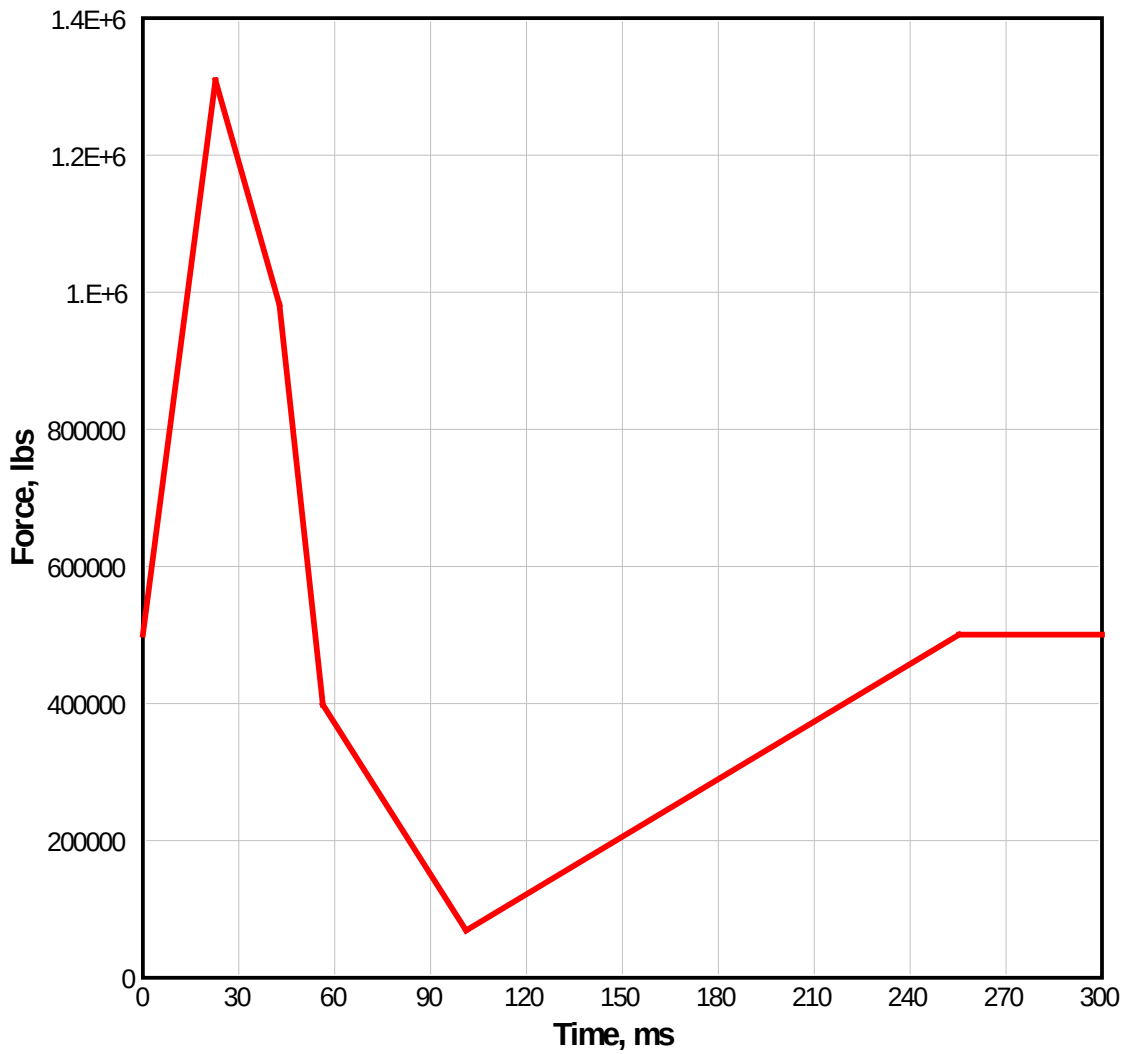
Step 4.

a. Calculate area of the roof.

Area (roof) = 30^2x $(12)^2$ = 129,600 in^2

b. Construct the downward force-time curve by multiplying the values of the roof curve from Step 1 by the roof area from Step 4a, and adding the dead weight of structure W_d = 500,600 lbs from Step 3a. (If the resulting value is negative, assume zero). See Figure 2A-27 (+) below.

Figure 2A-27



Step 5. Coefficient of friction μ from Table 2-12 (+) for coarse and compact soil.

μ = 0.60

Step 6. Using the acceleration impulse extrapolation method from Chapter 3 of this manual determine maximum horizontal acceleration, displacement and velocity of the structure due to load curve (P) from Step 2c. Resisting force R is the friction force produced due to the downward load curve F from Step 4b after an initial lateral translation of 1/4 inch. Use two ms time intervals for extrapolation. The following are the equations used in the extrapolation shown in Table 2A-3 (+).

$P_n - R_n = ma_n$

$R_n = \mu F_n$

$X_{n+1} = 2X_u - X_{n-1} + a_n (\delta t)^2$

$V_n = V_{n-1} + a_n (\delta t)$

where

P_n = Load at time of step n (Step 2c)

R_n = Resisting Friction Force at time step n

m = Mass (Step 3b)

a_n = Acceleration at time step n

μ = Friction coefficient (Step 5)

F_n = Downward force at time step n (Step 4b)

X_n = Deflection at time step n

V_n = Velocity at time step n

The maximum motions from Table 2A-3 (+) are:

a_{max} = 0.00122 in/ms^2 << 101.67 ft/sec^2 << 3.16 g's

V_{max} = 0.01231 in/ms << 1.026 ft/sec

D_{max} = 0.355 in

Table 2A-3

n	t ms	P_n lbs	R_n lbs	P_n-R_n lbs	$a_n = (P_n-R_n)/m$ in/ms^2	$a_n(\delta t)2$ in	$2X_n$ in	X_{n-1} in	X_{n+1} in	$a_n\delta t$ in/ms	V_{n-1} in/ms	V_n in/ms
0	0	1,781,208	0	1,781,208	(0.00138)/2	(0.00550)/2	0	0	0.00275	(0.00275)/2	0	0.00138
1	2	1,582,190	0	1,582,190	0.00122	0.00489	0.00550	0	0.01038	0.00244	0.00138	0.00382
2	4	1,383,173	0	1,383,173	0.00107	0.00427	0.02077	0.00275	0.02229	0.00214	0.00382	0.00596
3	6	1,184,155	0	1,184,155	0.00091	0.00366	0.04458	0.01038	0.03786	0.00182	0.00596	0.00778
4	8	985,137	0	985,137	0.00076	0.00304	0.07571	0.02229	0.05646	0.00152	0.00778	0.00930
5	10	786,120	0	786,120	0.00061	0.00243	0.11292	0.03786	0.07749	0.00122	0.00930	0.01052
6	12	587,102	0	587,102	0.00045	0.00181	0.15497	0.05646	0.10032	0.00090	0.01052	0.01142
7	14	388,084	0	388,084	0.00030	0.00120	0.20064	0.07749	0.12435	0.00060	0.01142	0.01202
8	16	189,067	0	189,067	0.00015	0.00058	0.24870	0.10032	0.14896	0.00029	0.01202	0.01231
9	18	0	0	0	0	0	0.29793	0.12435	0.17358	0	0.01231	0.01231
10	20	0	0	0	0	0	0.34716	0.14896	0.19820	0	0.01231	0.01231
11	22	0	0	0	0	0	0.39640	0.17358	0.22282	0	0.01231	0.01231
12	24	-50,013	0	-50,013	-0.00004	-0.00015	0.44564	0.19820	0.24728	-0.00008	0.01231	0.01223
13	26	-126,956	0	-126,956	-0.00010	-0.00039	0.49456	0.22282	0.27135	-0.00020	0.01223	0.01203
14	28	-203,890	733,536	-937,426	-0.00072	-0.00289	0.54270	0.24728	0.29253	-0.00142	0.01203	0.01061
15	30	-280,843	713,896	-994,739	-0.00077	-0.00307	0.58505	0.27135	0.310629	-0.00153	0.01061	0.00908
16	32	-357,786	694,256	-1,052,042	-0.00081	-0.00325	0.62126	0.29253	0.32548	-0.00162	0.00908	0.00746
17	34	-337,457	674,617	-1,012,074	-0.00078	-0.00312	0.65096	0.310629	0.33721	-0.00156	0.00746	0.00590
18	36	-317,128	654,977	-972,105	-0.00075	-0.00300	0.67441	0.32548	0.34593	-0.00150	0.00590	0.00440
19	38	-296,780	635,337	-932,117	-0.00072	-0.00288	0.69186	0.33721	0.35177	-0.00144	0.0044	0.00296
20	40	-276,471	615,697	-892,168	-0.00069	-0.00275	0.70354	0.34593	0.35486	-0.00138	0.00296	0.00158
21	42	-256,142	596,057	-852,199	-0.00066	-0.00263	0.70972	0.35177	0.35532	-0.00132	0.00158	0.00026
22	44	-240,745	555,710	-796,455	-0.00061	-0.00244	0.71064	0.35486	0.35332	-0.00122	0.00026	0.00096
23	46	-278,004	504,214				0.70664	0.35532				
24	48	-215,263	452,718				0.35332					

PROBLEM 2A-20 SHOCK RESPONSE SPECTRA

Problem: **Construct the elastic shock response spectra for the interior components of an above ground structure subject to an external explosion.**

Procedure:

Step 1. Determine maximum acceleration, velocity and displacement due to ground shock according to procedure outlined in Problem 2A-18.

Step 2. Determine maximum acceleration, velocity and displacement due to air shock according to the procedure outlined in Problems 2A-10 and 2A-19.

Step 3. Determine if the ground shock is outrunning or superseismic (Section 2-23.2). For outrunning ground shock the maximum values of displacement, velocity and acceleration in horizontal and vertical directions are the algebraic summation of the maximum motions from Steps 1 and 2. Otherwise proceed to Step 4.

Step 4. For superseismic ground shock the maximum values of displacement, velocity and acceleration are the numerically larger values of direct-induced ground shock or the algebraic sum of the maximum motions from air shock and airburst induced ground shock.

Step 5. Calculate the magnitude of acceleration, velocity and displacement for response spectra in horizontal and vertical directions by multiplying the maximum values of motions from Step 3 or Step 4 by their appropriate factor from Section 2-24.3.

Step 6. Draw the horizontal and vertical shock response spectras.

EXAMPLE 2A-20 SHOCK RESPONSE SPECTRA

Required: **Shock response spectra for the structure defined in Examples 2A-18 and 2A-19.**

Solution:

Step 1. Maximum values of motion in vertical and horizontal directions due to ground shock according to the procedure outlined in Example 2A-18 are:

a. Air blast-induced

$A_H = A_V = 3.44$ g

$V_H = V_V = 1.125$ in/sec

$D_H = D_V = 0.014$ in

b. Direct-induced

$A_H = 3.78$ g

$A_V = 7.56$ g

$V_H = V_V = 6.02$ in/sec

$D_H = D_V = .120$ in

Step 2. Maximum horizontal acceleration, velocity and displacement due to air shock following the procedure outlined in Examples 2A-10 and 2A-19.

$A_{max} = 3.16$ g

$V_{max} = 12.31$ in/sec

$D_{max} = 0.355$ in

Step 3.

a. Check for outrunning ground shock

$T_{AG} < T_A$:

From Example 2A-18

$T_{AG} = 26.6$ ms

$T_A = 60.9$ ms

$T_{AG} < T_A$ Outrunning ground shock

b. Add the values of maximum motions from Step 1 and Step 2.

$A_{H\,max}$ = 3.16 + 3.44 + 3.78 = 10.38 g

$V_{H\,max}$ = 12.310 + 1.108 + 6.020 = 19.438 in/sec

$D_{H\,max}$ = 0.355 + 0.014 + 0.120 = .489 in

and

$A_{V\,max}$ = 3.44 + 7.56 = 11.00 g

$V_{V\,max}$ = 1.108 + 6.020 = 7.128 in/sec

$D_{V\,max}$ = 0.014 + 0.120 = 0.134 in

Step 4. Does not apply, the ground shock is not superseismic.

Step 5. Magnitude of the motions for response spectra.

A_H = 10.38 x 2.0 = 20.76 g

V_H = 19.438 x 1.5 = 29.157 in/sec

D_H = 0.489 x 1.0 = 0.489 in

and

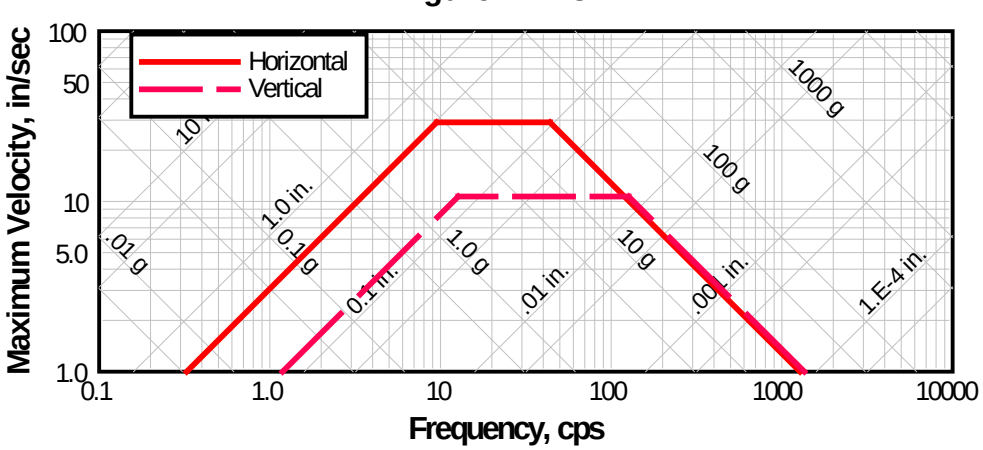
A_V = 11.00 x 2.0 = 22.00 g

V_V = 7.128 x 1.5 = 10.692 in/sec

D_V = 0.134 x 1.0 = 0.134 in

Step 6. See the shock response spectra for the values from Step 6 in Figure 2A-28 (+).

Figure 2A-28



APPENDIX 2B LIST OF SYMBOLS

a	(1) acceleration (in/ms^2)
	(2) depth of equivalent rectangular stress block (in)
	(3) long span of a panel (in)
a_o	velocity of sound in air (ft/sec)
a_x	acceleration in x direction (in/ms^2)
a_y	acceleration in y direction (in/ms^2)
A	(1) area (in^2)
	(2) explosive composition factor (oz$^{1/2}$-in$^{-3/2}$)
A_a	area of diagonal bars at the support within a width b (in^2)
A_b	area of reinforcing bar (in^2)
A_d	(1) door area (in^2)
	(2) area of diagonal bars at the support within a width b (in^2)
A_D	drag area (in^2)
A_f	net area of wall excluding openings (ft^2)
A_g	area of gross section (in^2)
A_H	maximum horizontal acceleration of the ground surface (g's)
A_l	area of longitudinal torsion reinforcement (in^2)
A_L	lift area (in^2)
A_n	(1) net area of section (in^2)
	(2) area of individual wall subdivision (ft^2)
A_o	area of openings (ft^2)
A_{ps}	area of prestressed reinforcement (in^2)
A_s	area of tension reinforcement within a width b (in^2)
A_s'	area of compression reinforcement within a width b (in^2)
A_s-	area of rebound reinforcement (in^2)

A_{sH}	area of flexural reinforcement within a width *b* in the horizontal direction on each face (in^2)*
A_{sp}	area of spiral reinforcement (in^2)
A_{st}	total area of reinforcing steel (in^2)
A_{sV}	area of flexural reinforcement within a width *b* in the vertical direction on each face (in^2)*
A_t	area of one leg of a closed tie resisting torsion within a distance *s* (in^2)
A_v	total area of stirrups or lacing reinforcement in tension within a distance, s_s or s_l and a width b_s or b_l (in^2)
A_V	maximum vertical acceleration of the ground surface (g's)
A_w	area of wall (ft^2)
A_I, A_{II}	area of sector I and II, respectively (in^2)
b	(1) width of compression face of flexural member (in)
	(2) width of concrete strip in which the direct shear stresses at the supports are resisted by diagonal bars (in)
	(3) short span of a panel (in)
b_f	width of fragment (in)
b_s	width of concrete strip in which the diagonal tension stresses are resisted by stirrups of area A_v (in)
b_l	width of concrete strip in which the diagonal tension stresses are resisted by lacing of area A_v (in)
b_o	failure perimeter for punching shear (in)
b_t	center-to-center dimension of a closed rectangular tie along *b* (in)
B	explosive constant defined in Table 2-7 (+) ($oz^{1/2}$ $in^{-7/6}$)
c	(1) distance from the resultant applied load to the axis of rotation (in)
	(2) damping coefficient
	(3) width of column capital (in)

* See note at end of symbols

c_I, c_{II}	distance from the resultant applied load to the axis of rotation for sectors I and II, respectively (in)
c_s	dilatational velocity of concrete (ft/sec)
C	(1) shear coefficient
	(2) deflection coefficient for flat slabs
C_C	deflection coefficient for the center of interior panel of flat slab
C_{cr}	critical damping
C_d	shear coefficient for ultimate shear stress of one-way elements
C_D	drag coefficient
$C_D q$	drag pressure (psi)
$C_D q_o$	peak drag pressure (psi)
C_E	equivalent load factor
C_f	post-failure fragment coefficient (lb^2-ms^4/in^8)
C_H	shear coefficient for ultimate shear stress in horizontal direction for two-way elements*
C_L	(1) leakage pressure coefficient from Figure 2-235 (+)
	(2) deflection coefficient for midpoint of long side of interior flat slab panel
	(3) lift coefficient
C_M	maximum shear coefficient
C_m	equivalent moment correction factor
C_p	compression wave seismic velocity in the soil from Table 2-10 (+) (in/sec)
C_r	sound velocity in reflected region from Figure 2-192 (+) (ft/ms)
C_R	force coefficient for shear at the corners of a window frame
$C_{r\alpha}$	peak reflected pressure coefficient at angle of incidence α
C_s	shear coefficient for ultimate support shear for one-way elements

* See note at end of symbols

C_{sH}	shear coefficient for ultimate support shear in horizontal direction for two-way elements*
C_{sV}	shear coefficient for ultimate support shear in vertical direction for two-way elements*
C_S	deflection coefficient for midpoint of short side of interior flat slab panel
C_u	impulse coefficient at deflection X_u (psi-ms^2/in^2)
C_u'	impulse coefficient at deflection X_m (psi-ms^2/in^2)
C_v	shear coefficient for ultimate shear stress in vertical direction for two-way elements*
C_x	shear coefficient for the ultimate shear along the long side of window frame
C_y	shear coefficient for the ultimate shear along the short side of window frame
C_L	confidence level
C_1	(1) impulse coefficient at deflection X_1 (psi-ms^2/in^2)
	(2) ratio of gas load to shock load
C_1'	impulse coefficient at deflection X_m (psi-ms^2/in^2)
C_2	ratio of gas load duration to shock load duration
d	(1) distance from extreme compression fiber to centroid of tension reinforcement (in)
	(2) diameter (in)
	(3) fragment diameter (in)
d'	distance from extreme compression fiber to centroid of compression reinforcement (in)
d_b	diameter of reinforcing bar (in)
d_c	distance between the centroids of the compression and tension reinforcement (in)
d_{cH}	distance between the centroids of the horizontal compression and tension reinforcement (in)
d_{co}	diameter of steel core (in)

* See note at end of symbols

d_{cV} distance between the centroids of the vertical compression and tension reinforcement (in)

d_e distance from support and equal to distance d or d_c (in)

d_i average inside diameter of explosive casing (in)

d_i' adjusted inside diameter of casing (in)

d_P distance between center lines of adjacent lacing bends measured normal to flexural reinforcement (in)

d_p distance from extreme compression fiber to centroid of prestressed reinforcement (in)

d_{sp} depth of spalled concrete (in)

d_1 diameter of cylindrical portion of primary fragment (in)

D (1) unit flexural rigidity (lb-in)

(2) location of shock front for maximum stress (ft)

(3) minimum magazine separation distance (ft)

(4) caliber density (lb/in^3)

(5) overall diameter of circular section (in)

(6) damping force (lb)

(7) displacement of mass from shock load (in)

D_E equivalent loaded width of structure for non-planar wave front (ft)

D_H maximum horizontal displacement of the ground surface (in)

DIF dynamic increase factor

D_s diameter of the circle through centers of reinforcement arranged in a circular pattern (in)

D_{sp} diameter of the spiral measured through the centerline of the spiral bar (in)

DLF dynamic load factor

D_V maximum vertical displacement of the ground surface (in)

e (1) base of natural logarithms and equal to 2.71828...

(2) distance from centroid of section to centroid of prestressed reinforcement (in)

	(3) actual eccentricity of load (in)
e_b	balanced eccentricity (in)
$(2E')^{1/2}$	Gurney Energy Constant (ft/sec)
E	(1) modulus of elasticity
	(2) internal work (in-lbs)
E_c	modulus of elasticity of concrete (psi)
E_m	modulus of elasticity of masonry units (psi)
E_s	modulus of elasticity of reinforcement (psi)
f	(1) unit external force (psi)
	(2) frequency of vibration (cps)
f_c'	static ultimate compressive strength of concrete at 28 days (psi)
f_{dc}'	dynamic ultimate compressive strength of concrete (psi)
f_{dm}'	dynamic ultimate compressive strength of masonry units (psi)
f_{ds}	dynamic design stress for reinforcement (a function of f_y, f_u and Θ) (psi)
f_{du}	dynamic ultimate stress of reinforcement (psi)
f_{dy}	dynamic yield stress of reinforcement (psi)
f_m'	static ultimate compressive strength of masonry units (psi)
f_n	natural frequency of vibration (cps)
f_{ps}	average stress in the prestressed reinforcement at ultimate load (psi)
f_{pu}	specified tensile strength of prestressing tendon (psi)
f_{py}	yield stress of prestressing tendon corresponding to a 1 percent elongation (psi)
f_r	reflection factor
f_s	static design stress for reinforcement (psi)
f_{se}	effective stress in prestressed reinforcement after allowances for all prestress losses (psi)
f_u	static ultimate stress of reinforcement (psi)
f_y	static yield stress of reinforcement (psi)

F	(1) total external force (lbs)
	(2) coefficient for moment of inertia of cracked section
	(3) function of C_2 and C_1 for bilinear triangular load
F_o	force in the reinforcing bars (lbs)
F_E	equivalent external force (lbs)
F_D	drag force (lbs)
F_F	frictional force (lbs)
F_L	lift force (lbs)
F_N	vertical load supported by foundation (lbs)
g	acceleration due to gravity (32.2 ft/sec^2)
G	shear modulus (psi)
h	(1) charge location parameter (ft)
	(2) height of masonry wall
h_n	average clearing distance for individual areas of openings from Section 2-15.4.2
h_t	center-to-center dimension of a closed rectangular tie along h (in)
h'	clear height between floor slab and roof slab
H	(1) span height (in)*
	(2) distance between reflecting surface(s) and/or free edge(s) in vertical direction (ft)
	(3) minimum transverse dimension of mean presented area of object (ft)
H_c	height of charge above ground (ft)
H_s	height of structure (ft)
H_T	height of triple point (ft)
H_w	height of wall (ft)
H_c	heat of combustion (ft-lb/lb)

* See note at end of symbols

H_d	heat of detonation (ft-lb/lb)
i	unit positive impulse (psi-ms)
i_a	sum of blast impulse capacity of the receiver panel and the least impulse absorbed by the sand (psi-ms)
i_{ba}	blast impulse capacity of receiver panel (psi-ms)
i^-	unit negative impulse (psi-ms)
$\overline{i_a}$	sum of scaled unit blast impulse capacity of receiver panel and scaled unit blast impulse attenuated through concrete and sand in a composite element (psi-ms/lb$^{1/3}$)
i_b	unit blast impulse (psi-ms)
$\overline{i_b}$	scaled unit blast impulse (psi-ms/lb$^{1/3}$)
$\overline{i_{ba}}$	scaled unit blast impulse capacity of receiver panel of composite element (psi-ms/lb$^{1/3}$)
$\overline{i_{bd}}$	scaled unit blast impulse capacity of donor panel of composite element (psi-ms/lb$^{1/3}$)
$\overline{i_{bt}}$	total scaled unit blast impulse capacity of composite element (psi-ms/lb$^{1/3}$)
i_c	impulse capacity of an element (psi-ms)
i_d	total drag and diffraction impulse (psi-ms)
i_e	unit excess blast impulse (psi-ms)
i_{fs}	required impulse capacity of fragment shield (psi-ms)
i_g	gas impulse (psi-ms)
i_r	unit positive normal reflected impulse (psi-ms)
i_r^-	unit negative normal reflected impulse (psi-ms)
$i_{r\alpha}$	peak reflected impulse at angle of incidence α (psi-ms)
i_s	unit positive incident impulse (psi-ms)
i_s^-	unit negative incident impulse (psi-ms)
i_{st}	impulse consumed by fragment support connection (psi-ms)

I	(1) moment of inertia (in^4/in for slabs) (in^4 for beams)
	(2) total impulse applied to fragment
I_a	average of gross and cracked moments of inertia (in^4/in for slabs) (in^4 for beams)
I_c	moment of inertia of cracked concrete section (in^4/in for slabs) (in^4 for beams)
I_{cH}	moment of inertia of cracked concrete section in horizontal direction (in^4/in)*
I_{cV}	moment of inertia of cracked concrete section in vertical direction (in^4/in)*
I_g	moment of inertia of gross concrete section (in^4/in for slabs) (in^4 for beams)
I_m	mass moment of inertia (lb-ms^2-in)
I_n	moment of inertia of net section of masonry unit (in^4)
I_s	gross moment of inertia of slab (in^4/in)
I_{st}	impulse consumed by the fragment support connection (psi-ms)
I_w	gross moment of inertia of wall (in^4/in)
j	ratio of distance between centroids of compression and tension forces to the depth d
k	(1) constant depending on the casing metal
	(2) effective length factor
k_v	velocity decay coefficient
K	(1) unit stiffness (psi/in for slabs) (lb/in/in for beams) (lb/in for springs)
	(2) constant defined in Section 2-18.2
K_e	elastic unit stiffness (psi/in for slabs) (lb/in/in for beams)
K_{ep}	elasto-plastic unit stiffness (psi/in for slabs) (lb/in/in for beams)
K_E	(1) equivalent elastic unit stiffness (psi/in for slabs) (lb/in/in for beams)
	(2) equivalent spring constant (lb/in)
K_L	load factor
K_{LM}	load-mass factor

* See note at end of symbols

$(K_{LM})_u$	load-mass factor in the ultimate range
$(K_{LM})_{up}$	load-mass factor in the post-ultimate range
K_M	mass factor
K_R	resistance factor
K_E	kinetic energy
l	charge location parameter (ft)
l	(1) length of the yield line (in)
	(2) width of 1/2 of the column strip (in)
l_d	basic development length of reinforcing bar (in)
l_{dh}	development length of hooked bar (in)
l_c	length of cylindrical explosive (in)
l_p	spacing of same type of lacing bar (in)
l_s	span of flat slab panel (in)
L	(1) span length (in)*
	(2) distance between reflecting surface(s) and/or free edge(s) in horizontal direction (ft)
L_{cyl}	length of cylinder (in)
L_f	length of fragment (in)
L_H	clear span in short direction (in)
L_l	length of lacing bar required in distance s_l (in)
L_L	clear span in long direction (in)
L_o	embedment length of reinforcing bars (in)
L_u	unsupported length of column (in)
L_w	wave length of positive pressure phase (ft)
L_w^-	wave length of negative pressure phase (ft)

* See note at end of symbols

L_x	clear span in long direction (in)
L_y	clear span in short direction (in)
L_{wb}, L_{wd}	wave length of positive pressure phase at points *b* and *d*, respectively (ft)
L_1	total length of sector of element normal to axis of rotation (in)
m	(1) unit mass (psi-ms^2/in for slabs) [beams, (lb/in-ms^2)/in]
	(2) ultimate unit moment (in-lbs/in)
	(3) mass of fragment (lbs-ms^2/in)
m_a	average of the effective elastic and plastic unit masses (psi-ms^2/in for slabs) [beams, (lb/in-ms^2)/in]
m_e	effective unit mass (psi-ms^2/in for slabs) [beams, (lb/in-ms^2)/in]
m_{sp}	mass of spalled fragments (psi-ms^2/in)
m_u	effective unit mass in the ultimate range (psi-ms^2/in for slabs) [beams, (lb/in-ms^2)/in]
m_{up}	effective unit mass in the post-ultimate range (psi-ms^2/in)
M	(1) unit bending moment (in-lbs/in for slabs) (in-lbs for beams)
	(2) total mass (lb-ms^2/in)
	(3) design moment (in-lbs)
M_e	effective total mass (lb-ms^2/in)
M_u	ultimate unit resisting moment (in-lbs/in for slabs) (in-lbs for beams)
M_u^-	ultimate unit rebound moment (in-lbs/in for slabs) (in-lbs for beams)
M_c	moment of concentrated loads about line of rotation of sector (in-lbs)
M_A	fragment distribution factor
M_E	equivalent total mass (lb-ms^2/in)
M_{HN}	ultimate unit negative moment capacity in horizontal direction (in-lbs/in)*
M_{HP}	ultimate unit positive moment capacity in horizontal direction (in-lbs/in)*
M_{OH}, M_{OL}	total panel moment for direction *H* and *L* respectively (in-lbs)

* See note at end of symbols

M_N	ultimate unit negative moment capacity at supports (in-lbs/in for slabs) (in-lbs for beams)
M_P	ultimate unit positive moment capacity at midspan (in-lbs/in for slabs) (in-lbs for beams)
M_{VN}	ultimate unit negative moment capacity in vertical direction (in-lbs/in)*
M_{VP}	ultimate unit positive moment capacity in vertical direction (in-lbs/in)*
M_1	value of smaller end moment on column
M_2	value of larger end moment on column
n	(1) modular ratio
	(2) number of time intervals
	(3) number of glass pane tests
	(4) caliber radius of the tangent ogive of fragment nose
N	(1) number of adjacent reflecting surfaces
	(2) nose shape factor
N_f	number of primary fragments larger than W_f
N_u	axial load normal to the cross section
N_T	total number of fragments
p	reinforcement ratio equal to A_s/bd or A_s/bd_c
p'	reinforcement ratio equal to A_s'/bd or A_s'/bd_c
p_b	reinforcement ratio producing balanced conditions at ultimate strength
p_o	ambient atmospheric pressure (psi)
p_p	prestressed reinforcement ratio equal to A_{ps}/bd_p
p_m	mean pressure in a partially vented chamber (psi)
p_{mo}	peak mean pressure in a partially vented chamber (psi)
p_r	average peak reflected pressure (psi)
p_H	reinforcement ratio in horizontal direction on each face*

* See note at end of symbols

p_T	total reinforcement ratio equal to $p_H + p_V$
p_V	reinforcement ratio in vertical direction on each face*
$p(x)$	distributed load per unit length
P	(1) pressure (psi)
	(2) concentrated load (lbs)
P^-	negative pressure (psi)
P_c	critical axial load causing buckling (lbs)
P_g	maximum gas pressure (psi)
P_i	interior pressure within structure (psi)
δP_i	interior pressure increment (psi)
P_f	fictitious peak pressure (psi)
P_{max}	maximum average pressure acting on interior face of wall (psi)
P_o	(1) peak pressure (psi)
	(2) maximum axial load (lbs)
	(3) atmospheric pressure (psi)
P_r	peak positive normal reflected pressure (psi)
P_r^-	peak negative normal reflected pressure (psi)
$P_{r\alpha}$	peak reflected pressure at angle of incidence α (psi)
P_{RIB}	maximum average pressure on backwall (psi)
P_s	positive incident pressure (psi)
P_{sb}, P_{se}	positive incident pressure at points *b* and *e*, respectively (psi)
P_{so}	peak positive incident pressure (psi)
P_{so}^-	peak negative incident pressure (psi)
P_{sob}, P_{sod}, P_{soe}	peak positive incident pressure at points *b*, *d* and *e*, respectively (psi)
P_u	ultimate axial load at actual eccentricity *c* (lbs)
P_x	ultimate load when eccentricity e_x is present (lbs)
P_y	ultimate load when eccentricity e_y is present (lbs)

q	dynamic pressure (psi)
q_b, q_e	dynamic pressure at points *b* and *e*, respectively (psi)
q_o	peak dynamic pressure (psi)
q_{ob}, q_{oe}	peak dynamic pressure at points *b* and *e*, respectively (psi)
r	(1) unit resistance (psi)
	(2) radius of spherical TNT (density equals 95 lb/ft^3) charge (ft)
	(3) radius of gyration of cross section of column (in)
r^-	unit rebound resistance (psi, for slabs) (lb/in for beams)
r_{avail}	dynamic resistance available (psi)
δr	change in unit resistance (psi, for slabs) (lb/in for beams)
r_d	radius from center of impulse load to center of door rotation (in)
r_{DL}	uniform dead load (psi)
r_e	elastic unit resistance (psi, for slabs) (lb/in for beams)
r_{ep}	elasto-plastic unit resistance (psi, for slabs) (lb/in for beams)
r_{fs}	ultimate unit resistance of fragment shield (psi)
r_T	tension membrane resistance (psi)
r_u	ultimate unit resistance (psi, for slabs) (lb/in for beams)
r_{up}	post-ultimate unit resistance (psi)
r_1	radius of hemispherical portion of primary fragment (in)
R	(1) total internal resistance (lbs)
	(2) slant distance (ft)
	(3) ratio of *S*/*G*
	(4) standoff distance (ft)
R_{eff}	effective radius (ft)
R_f	(1) distance traveled by primary fragment (ft)
	(2) distance from center of detonation (ft)
R_g	uplift force at corners of window frame (lbs)

R_l	radius of lacing bend (in)
R_t	target radius (ft)
R_A	normal distance (ft)
R_E	equivalent total internal resistance (lbs)
R_G	ground distance (ft)
R_u	total ultimate resistance (lb)
R_{I}, R_{II}	total internal resistance of sectors I and II, respectively (lbs)
s	(1) sample standard deviation
	(2) spacing of torsion reinforcement in a direction parallel to the longitudinal reinforcement (in)
	(3) pitch of spiral (in)
s_s	spacing of stirrups in the direction parallel to the longitudinal reinforcement (in)
s_1	spacing of lacing in the direction parallel to the longitudinal reinforcement (in)
S	height of front wall or one-half its width, whichever is smaller (ft)
S'	weighted average clearing distance with openings (ft)
SE	strain energy
t	time (ms)
δt	time increment (ms)
t_a	any time (ms)
t_b, t_e, t_f	time of arrival of blast wave at points *b*, *e* and *f*, respectively (ms)
t_c	(1) clearing time for reflected pressures (ms)
	(2) average casing thickness of explosive charges (in)
t_c'	(1) adjusted casing thickness (in)
	(2) clearing time for reflected pressures adjusted for wall openings (ms)
t_d	rise time (ms)
t_E	time to reach maximum elastic deflection (ms)

t_g	fictitious gas duration (ms)
t_m	time at which maximum deflection occurs (ms)
t_o	duration of positive phase of blast pressure (ms)
t_o^-	duration of negative phase of blast pressure (ms)
t_{of}	fictitious positive phase pressure duration (ms)
t_{of}^-	fictitious negative phase pressure duration (ms)
t_{rf}	fictitious reflected pressure duration (ms)
t_u	time at which ultimate deflection occurs (ms)
t_y	time to reach yield (ms)
t_A	time of arrival of blast wave (ms)
t_{AG}	time of arrival of ground shock (ms)
t_1	time at which partial failure occurs (ms)
T	(1) duration of equivalent triangular loading function (ms)
	(2) thickness of masonry wall (in)
	(3) toughness of material (psi-in/in)
T_c	thickness of concrete section (in)
$\overline{T_c}$	scaled thickness of concrete section (ft/lb$^{1/3}$)
T_g	thickness of glass (in)
T_H	force in the continuous reinforcement in the short span direction (lbs)
T_i	angular impulse load (lb-ms-in)
T_L	force in the continuous reinforcement in the long span direction (lbs)
T_N	effective natural period of vibration (ms)
T_{pf}	minimum thickness of concrete to prevent perforation by a given fragment (in)
T_r	rise time (ms)
T_s	(1) thickness of sand fill (in)
	(2) thickness of slab (in)

T_{sp}	minimum concrete thickness to prevent spalling (in)
$\overline{T_s}$	scaled thickness of sand fill (ft/lb$^{1/3}$)
T_u	total torsional moment at critical section (in-lbs)
T_w	thickness of wall (in)
T_y	force of the continuous reinforcement in the short direction (lbs)
u	particle velocity (ft/ms)
u_u	ultimate flexural or anchorage bond stress (psi)
U	shock front velocity (ft/ms)
U_s	strain energy
v	velocity (in/ms)
v_a	instantaneous velocity at any time (in/ms)
v_b	boundary velocity for primary fragments (ft/sec)
v_c	ultimate shear stress permitted on an unreinforced web (psi)
v_f	maximum post-failure fragment velocity (in/ms)
v_f (avg)	average post-failure fragment velocity (in/ms)
v_i	velocity at incipient failure deflection (in/ms)
v_o	initial velocity of primary fragment (ft/sec)
v_r	residual velocity of primary fragment after perforation (ft/sec)
v_s	striking velocity of primary fragment (ft/sec)
v_{tc}	maximum torsion capacity of an unreinforced web (psi)
v_{tu}	nominal torsion stress in the direction of v_u (psi)
v_u	ultimate shear stress (psi)
v_{uH}	ultimate shear stress at distance d_e from the horizontal support (psi)*
v_{uV}	ultimate shear stress at distance d_e from the vertical support (psi)*
v_x	velocity in x direction (in/ms)

* See note at end of symbols

v_y	velocity in *y* direction (in/ms)
V	(1) volume of partially vented chamber (ft^3)
	(2) velocity of compression wave through concrete (in/sec)
	(3) velocity of mass under shock load (in/sec)
V_d	ultimate direct shear capacity of the concrete of width *b* (lbs)
V_{dH}	shear at distance d_e from the vertical support on a unit width (lbs/in)*
V_{dV}	shear at distance d_e from the horizontal support on a unit width (lbs/in)*
V_f	free volume (ft^3)
V_H	maximum horizontal velocity of the ground surface (in/sec)
V_o	volume of structure (ft^3)
V_s	shear at the support (lb/in for panels) (lbs for beam)
V_{sH}	shear at the vertical support on a unit width (lbs/in)*
V_{sV}	shear at the horizontal support on a unit width (lbs/in)*
V_u	total shear on a width *b* (lbs)
V_V	maximum vertical velocity of the ground surface (in/sec)
V_x	unit shear along the long side of window frame (lb/in)
V_y	unit shear along the short side of window frame (lbs/in)
w	applied uniform load (lbs-in^2)
w_c	(1) unit weight (psi for panels) (lb/in for beam)
	(2) weight density of concrete (lbs/ft^3)
w_s	weight density of sand (lbs/ft^3)
W	(1) design charge weight (lbs)
	(2) external work (in-lbs)
	(3) width of wall (ft)
W_A	weight of fluid (lbs)
W_{ACT}	actual quantity of explosives (lbs)
W_c	total weight of explosive containers (lbs)

W_E	effective charge weight (lbs)
W_{Eg}	effective charge weight for gas pressure (lb)
W_{EXP}	weight of explosive in question (lbs)
W_f	weight of primary fragment (oz)
$\overline{W_f}$	average fragment weight (oz)
W_F	weight of frangible element (lb/ft^2)
W_{CI}	weight of inner casing (lbs)
W_{co}	total weight of steel core (lbs)
W_{CO}	weight of outer casing (lbs)
W_{c1}, W_{c2}	total weight of plates 1 and 2, respectively (lbs)
W_s	width of structure (ft)
W_D	work done
x	yield line location in horizontal direction (in)*
X	(1) deflection (in) (2) distance from front of object to location of largest cross section to plane of shock front (ft)
X_a	any deflection (in)
X_c	lateral deflection to which a masonry wall develops no resistance (in)
X_{DL}	deflection due to dead load (in)
X_e	elastic deflection (in)
X_E	equivalent elastic deflection (in)
X_{ep}	elasto-plastic deflection (in)
X_f	maximum penetration into concrete of armor-piercing fragments (in)
X_f'	maximum penetration into concrete of fragments other than armor-piercing (in)
X_m	maximum transient deflection (in)

* See note at end of symbols

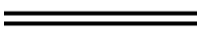
X_p	plastic deflection (in)
X_s	(1) maximum penetration into sand of armor-piercing fragments (in)
	(2) static deflection (in)
X_u	ultimate deflection (in)
X_1	(1) partial failure deflection (in)
	(2) deflection at maximum ultimate resistance of masonry wall (in)
y	yield line location in vertical direction (in)*
y_t	distance from the top of section to centroid (in)
Z	scaled slant distance (ft/lb$^{1/3}$)
Z_A	scaled normal distance (ft/lb$^{1/3}$)
Z_G	scaled ground distance (ft/lb$^{1/3}$)
α	(1) angle formed by the plane of stirrups, lacing, or diagonal reinforcement and the plane of the longitudinal reinforcement (deg)
	(2) angle of incidence of the pressure front (deg)
	(3) acceptance coefficient
	(4) trajectory angle (deg)
α_{ec}	ratio of flexural stiffness of exterior wall to flat slab
α_{ecH}, α_{ecL}	ratio of flexural stiffness of exterior wall to slab in direction *H* and *L* respectively
ß	(1) coefficient for determining elastic and elasto-plastic resistances
	(2) particular support rotation angle (deg)
	(3) rejection coefficient
	(4) target shape factor from Figure 2-212 (+/+)
$ß_1$	factor equal to 0.85 for concrete strengths up to 4000 psi and is reduced by 0.05 for each 1000 psi in excess of 4000 psi
γ	coefficient for determining elastic and elasto-plastic deflections

* See note at end of symbols

γ_p	factor for type of prestressing tendon
δ	moment magnifier
δ_n	clearing factor
δ	deflection at sector's displacement (in)
ε_c'	average strain rate for concrete (in/in/ms)
ε_m	unit strain in mortar (in/in)
ε_s'	average strain rate for reinforcement (in/in/ms)
ε_u	rupture strain (in/in/ms)
Θ	(1) support rotation angle (deg)
	(2) angular acceleration (rad/ms^2)
Θ_{max}	maximum support rotation angle (deg)
Θ_H	horizontal rotation angle (deg)*
Θ_V	vertical rotation angle (deg)*
μ	(1) ductility factor
	(2) coefficient of friction
ν	Poisson's ratio
ρ	(1) mass density (lbs-ms^2/in^4)
	(2) density of air behind shock front (lbs/ft^3)
ρ_a	density of air (oz/in^3)
ρ_c	density of casing (oz/in^3)
ρ_f	mass density of fragment (oz/in^3)
ρ_o	mass density of medium (lb-ms^2/in^4)
σ_u	fracture strength of concrete (psi)
Σ_o	effective perimeter of reinforcing bars (in)

* See note at end of symbols

ΣM	summation of moments (in-lbs)
ΣM_N	sum of the ultimate unit resisting moments acting along the negative yield lines (in-lbs)
ΣM_P	sum of the ultimate unit resisting moments acting along the positive yield lines (in-lbs)
ϕ	(1) capacity reduction factor
	(2) bar diameter (in)
	(3) TNT conversion factor
ϕ_r	assumed shape function for concentrated loads
$\phi(x)$	assumed shape function for distributed loads free edge

 simple support

fixed support

either fixed, restrained, or simple support

* Note. This symbol was developed for two-way elements which are used as walls. When roof slabs or other horizontal elements are under consideration, this symbol will also be applicable if the element is treated as being rotated into a vertical position.

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