GLASS–BR

Software for the design and risk assessment of glass facades subjected to blast loading

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1 DESIGN METHODOLOGY "D1"

- Input data
- Three second duration (ASTM 2009b)
- Non–factored load (ASTM 2009a; Beason et al. 1998)
- Load resistance (ASTM 2009a)
- Probability of glass breakage (ASTM 2009a)

1.1 Input Data

General Geometry			
Long side (*a*)		1600.00	mm
Short side (*b*)		1200.00	mm
Glazing type		Insulating glass unit (IG)	
Nominal thickness: lite-1		8.00	mm
Glass type (PVB laminate): lite-1		HS (heat strengthened)	
Nominal thickness: lite-2		8.00	mm
Glass type (PVB laminate): lite-2		HS (heat strengthened)	
Boundary Conditions		4 sides supported	
Response Type		Flexural	

Mechanical Properties			
Elastic modulus (E)		7.17E+07	kPa
Surface flaw parameter (m)		7.00E+00	
Surface flaw parameter (k)		2.86E-53	$N^{-7}m^{12}$

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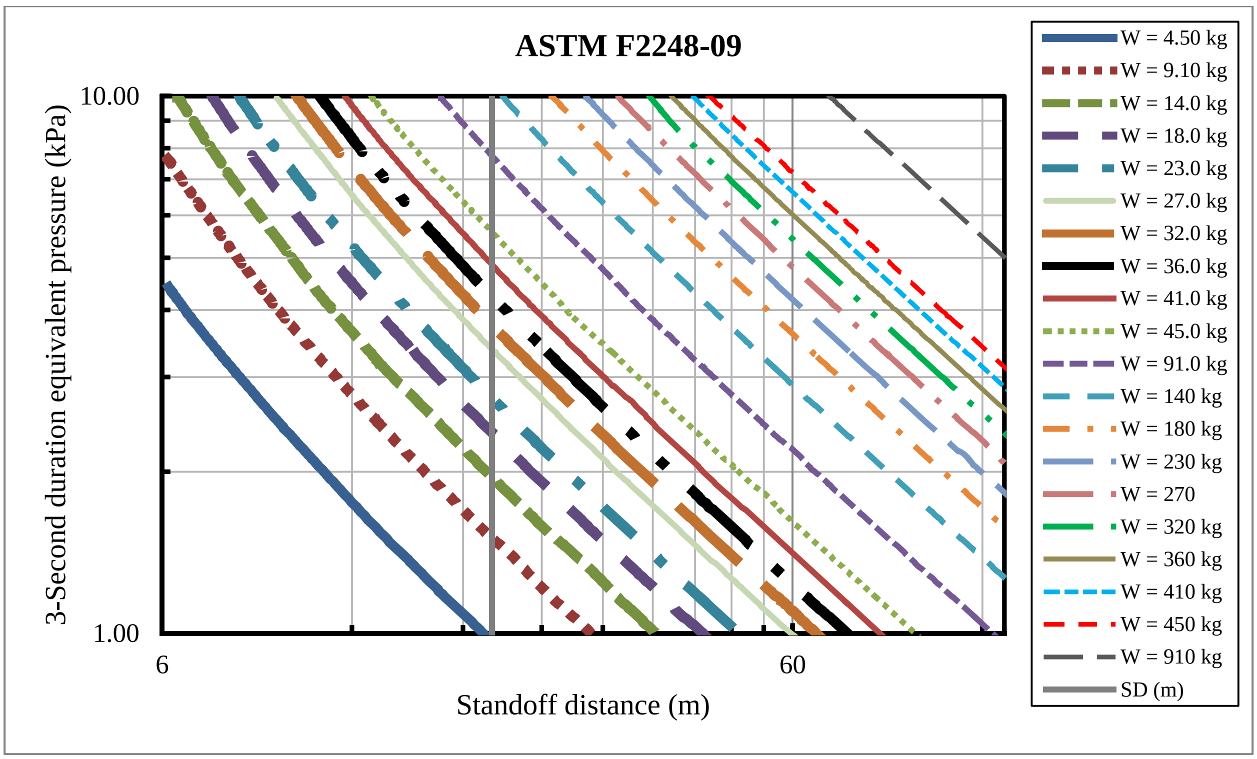
Target Probability of Breakage			
P_b-tolerable		8.00	/1000

Charge Weight & Standoff	
W (kg)	40.00
Explosive	TNT
TNT eq. factor	1.00
SD_x (m)	20.00
SD_y (m)	0.00
SD_z (m)	0.00

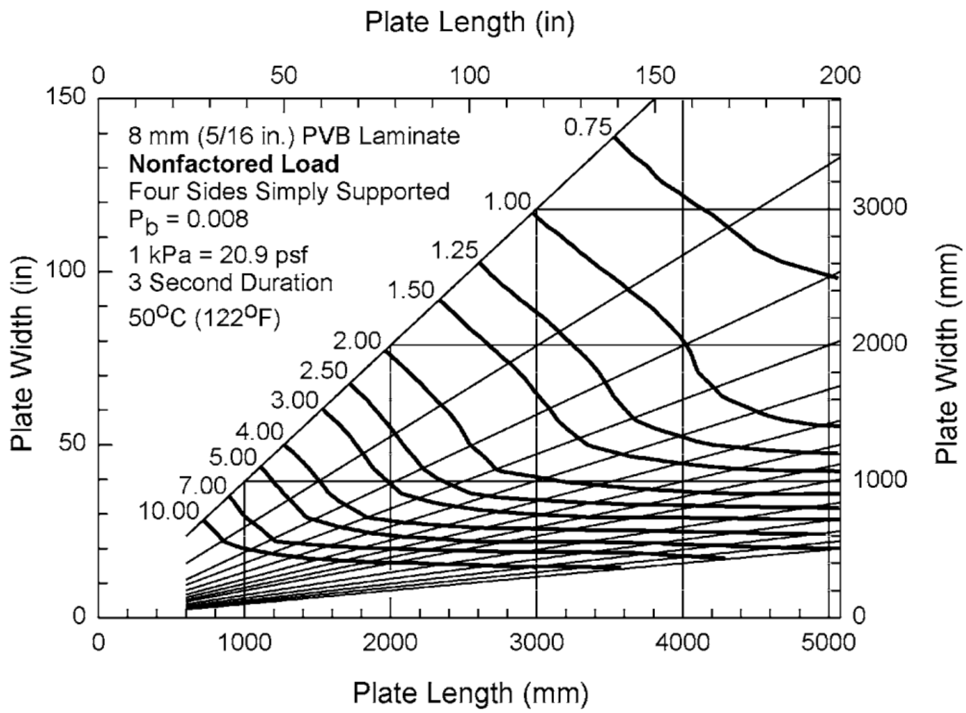
1.2 Three–Second Duration equivalent design pressure (TSD or *q*)

- Convert given explosive mass in equivalent mass of TNT: $W_{TNT} = W_{ex} \times TNT_{eq}$
- Calculate slanted standoff distance: $SD = \sqrt{SD_x^2 + SD_y^2 + SD_z^2}$
- Enter chart below to determine TSD



1.3 Non–Factored Load (NFL)

Use applicable design chart from ASTM E1300-09, depending on nominal thickness and boundary conditions.



1.4 Glass Type Factor (GTF)

Use Tables 1 or 2 from ASTM E-1300-09, depending on glazing type (single lite or IG unit)

TABLE 1 Glass Type Factors (GTF) for a Single Lite of Monolithic or Laminated Glass (LG)

Glass Type	GTF	
	Short Duration Load (3 s)	Long Duration Load (30 days)
AN	1.0	0.43
HS	2.0	1.3
FT	4.0	3.0

TABLE 2 Glass Type Factors (GTF) for Double Glazed Insulating Glass (IG), Short Duration Load

Lite No. 1 Monolithic Glass or Laminated Glass Type	Lite No. 2 Monolithic Glass or Laminated Glass Type					
	AN		HS		FT	
	GTF1	GTF2	GTF1	GTF2	GTF1	GTF2
AN	0.9	0.9	1.0	1.9	1.0	3.8
HS	1.9	1.0	1.8	1.8	1.9	3.8
FT	3.8	1.0	3.8	1.9	3.6	3.6

1.5 True (minimum) thickness (*h*)

ASTM E1300-09 Table 4	
Nominal thickness (mm)	**Minimum thickness (mm)**
2.50	2.16
2.70	2.59
3.00	2.92
4.00	3.78
5.00	4.57
6.00	5.56
8.00	7.42
10.00	9.02
12.00	11.91
16.00	15.09
19.00	18.26
22.00	21.44

1.6 Load Sharing Factors for IG unit (LSF)

Lite No. 1:

$$\mathrm{LSF}_1 = \frac{h_1^3 + h_2^3}{h_1^3} \tag{1}$$

Lite No. 2:

$$\mathrm{LSF}_2 = \frac{h_1^3 + h_2^3}{h_2^3} \tag{2}$$

For single lite glazing, LSF = 1.0.

1.7 Load resistance (LR)

$$\mathrm{LR} = \mathrm{NFL} \times \mathrm{GTF} \times \mathrm{LSF} \tag{3}$$

In case of IG unit:

$$\begin{aligned} \mathrm{LR}_1 &= \mathrm{NFL}_1 \times \mathrm{GTF}_1 \times \mathrm{LSF}_1 \\ \mathrm{LR}_2 &= \mathrm{NFL}_2 \times \mathrm{GTF}_2 \times \mathrm{LSF}_2 \\ \mathrm{LR} &= \min\{\mathrm{LR}_1, \mathrm{LR}_2\} \end{aligned} \tag{4}$$

1.8 Design requirement

$$\mathrm{LR} \geq q \tag{5}$$

2 Probability of Glass Breakage

- Non–dimensional load (ASTM 2009a; Beason et al. 1998)
- Aspect ratio
- Stress distribution factor (ASTM 2009a)
- Probability of failure (ASTM 2009a)

2.1 Aspect ratio (*a*/*b*)

$$a / b = \frac{a}{b} \tag{6}$$

2.2 Non–dimensional load ($\hat{q}$)

Lite–1:

$$\hat{q}_1 = \frac{q(ab)^2}{Eh_1^4} \frac{1}{\mathrm{GTF}_1} \frac{1}{\mathrm{LSF}_1} \tag{7}$$

Lite–2:

$$\hat{q}_2 = \frac{q(ab)^2}{Eh_2^4} \frac{1}{\mathrm{GTF}_2} \frac{1}{\mathrm{LSF}_2} \tag{8}$$

Units:

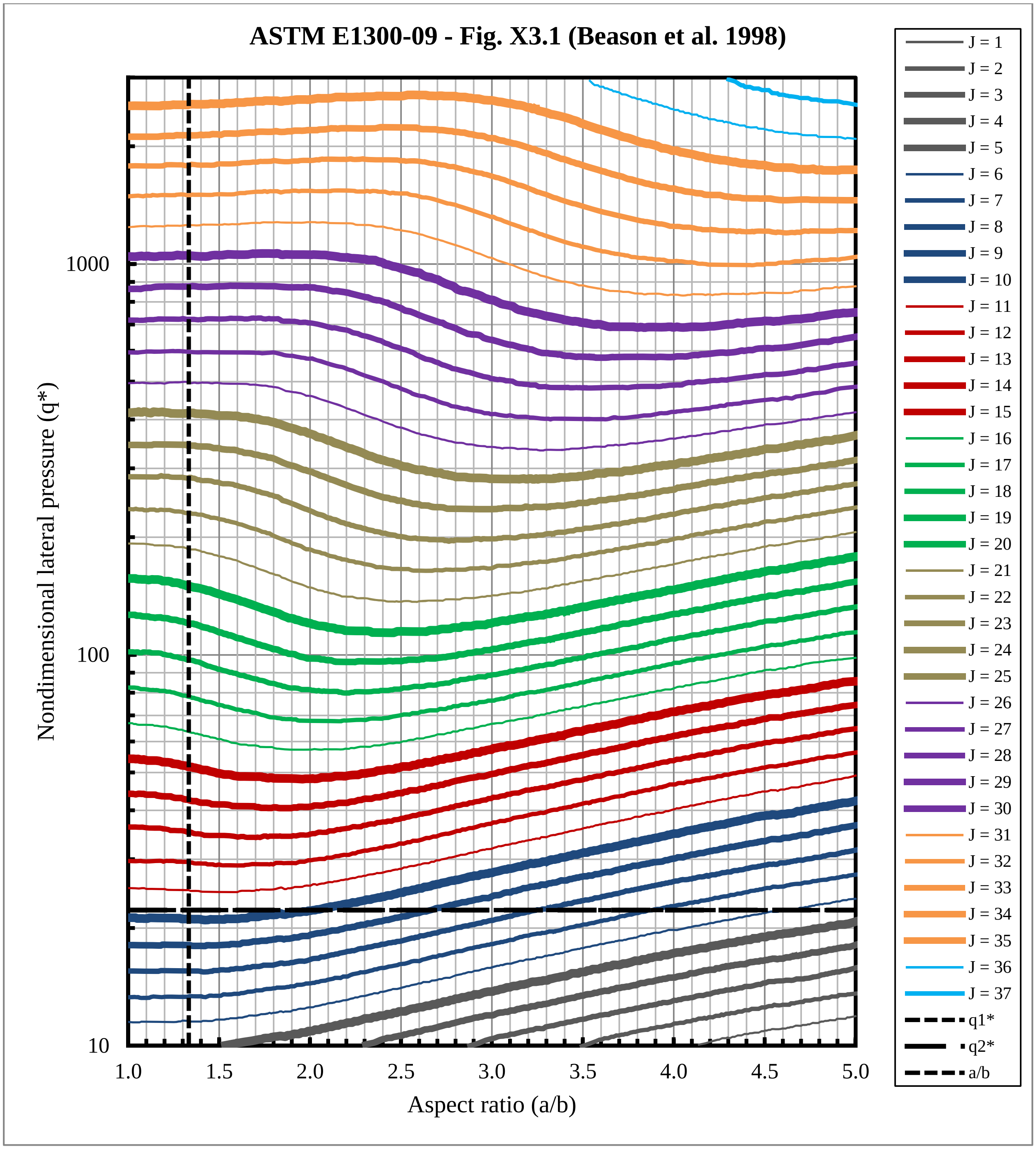
- [a] = [b] = [h] = m or mm
- [q] = [E] = Pa or kPa

2.2.1 Stress Distribution Factor (SDF or J)

Use Fig. X3.1 from ASTM E1300-09 to determine J from $\hat{q}$.

$$J_1 = J(\hat{q}_1) \tag{9}$$

$$J_2 = J(\hat{q}_2) \tag{10}$$



2.3 Probability of failure

$$P_b = \max\{P_{b1}, P_{b2}\} \tag{11}$$

$$P_{b1} = 1 - \exp[-B_1] = \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n!} B_1^n = B_1 - \frac{B_1^2}{2} + \frac{B_1^3}{6} - \frac{B_1^4}{24} + \ldots \approx B_1 \text{ (if } B_1 < 0.05) \tag{12}$$

$$P_{b2} = 1 - \exp\left[-B_2\right] \approx B_2 \tag{13}$$

$$B_1 = \frac{k}{(ab)^{m-1}} \left(Eh_1^2\right)^m \exp\left[J_1\left(m, \hat{q}_1, \frac{a}{b}\right)\right] \mathrm{LDF} \tag{14}$$

$$B_2 = \frac{k}{(ab)^{m-1}} \left(Eh_2^2\right)^m \exp\left[J_2\left(m, \hat{q}_2, \frac{a}{b}\right)\right] \mathrm{LDF} \tag{15}$$

$$\mathrm{LDF} = \left(\frac{t_d}{60}\right)^{\frac{m}{16}} \tag{16}$$

LDF = Load Duration Factor

Units:

- $[a] = [b] = [h]$ = m (meters)
- $[k]$ = $N^{-7}m^{12}$
- $[E]$ = Pa = N/m^2
- $[t_d]$ = s (3 seconds)

2.4 Design requirement

$$P_b \leq P_{b-tol} = 0.008 \tag{17}$$

3 DESIGN METHODOLOGY "D2"

This methodology is applicable for any selected value of the tolerable probability of glass breakage, whereas methodology "D1" is based on design charts that assume P_{b-tol} = 8/1000:

- Select tolerable probability of breakage (usually ≤ 8/1000)
- Calculate SDF associated with tolerable probability of failure
- Calculate non–factored load (ASTM 2009a; Beason et al. 1998)
- Calculate load resistance (ASTM 2009a)

3.1 Tolerable probability of breakage (P_{b-tol})

Select any value between 0 and 1. Usually, P_{b-tol} = 8/1000

3.2 Stress Distribution Factor associated with P_{b-tol}

From Eqs. (12), (14), and (16):

Lite–1:
$$J_{tol-1} = J\left(P_{b-tol}, h_1\right) = \ln\left[\ln\left(\frac{1}{1-P_{b-tol}}\right)\frac{(ab)^{m-1}}{k\left(Eh_1^2\right)^m}\left(\frac{60}{t_d}\right)^{\frac{m}{16}}\right] \tag{18}$$

Lite–2:
$$J_{tol-2} = J\left(P_{b-tol}, h_2\right) = \ln\left[\ln\left(\frac{1}{1-P_{b-tol}}\right)\frac{(ab)^{m-1}}{k\left(Eh_2^2\right)^m}\left(\frac{60}{t_d}\right)^{\frac{m}{16}}\right] \tag{19}$$

3.3 Non–factored load

Given J_{tol} above and a/b, use Fig. X3.1 from ASTM E-1300 to interpolate the value of the non–dimensional load ($\hat{q}$). Then, invert Eqs. (7) and (8) to find the NFL:

$$\mathrm{NFL}_1 = \frac{q_1}{\mathrm{GTF}_1\,\mathrm{LSF}_1} = \hat{q}_1\,\frac{Eh_1^4}{(ab)^2} \tag{20}$$

$$\mathrm{NFL}_2 = \frac{q_2}{\mathrm{GTF}_2\,\mathrm{LSF}_2} = \hat{q}_2\,\frac{Eh_2^4}{(ab)^2} \tag{21}$$

3.4 Load Resistance

$$\mathrm{LR}_1 = q_1 = \left(\mathrm{NFL}_1\right)\left(\mathrm{GTF}_1\right)\left(\mathrm{LSF}_1\right) \tag{22}$$

$$\mathrm{LR}_2 = q_2 = \left(\mathrm{NFL}_2\right)\left(\mathrm{GTF}_2\right)\left(\mathrm{LSF}_2\right) \tag{23}$$

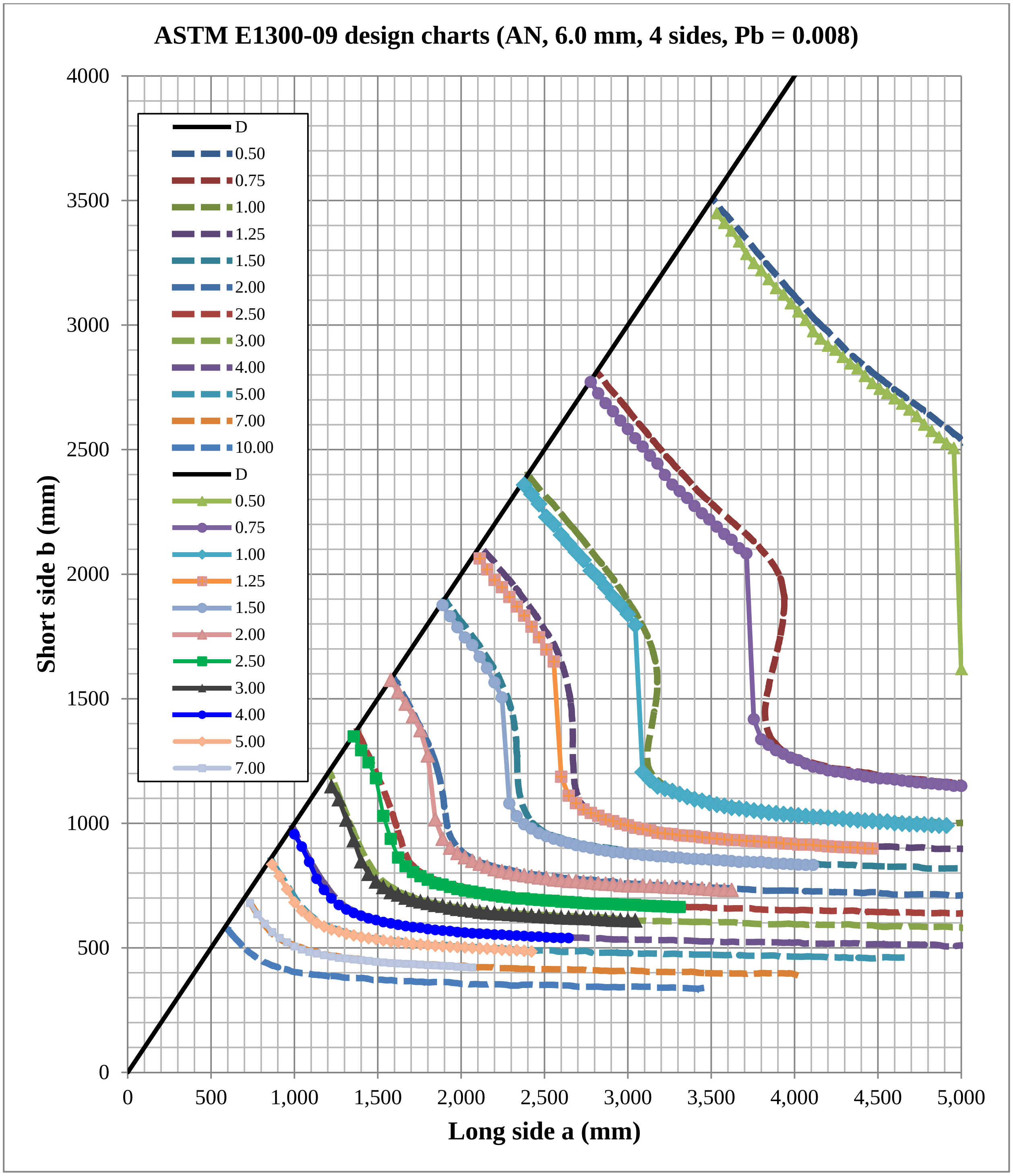
$$\mathrm{LR} = \min\left\{\mathrm{LR}_1, \mathrm{LR}_2\right\} \tag{24}$$

3.5 Design requirement

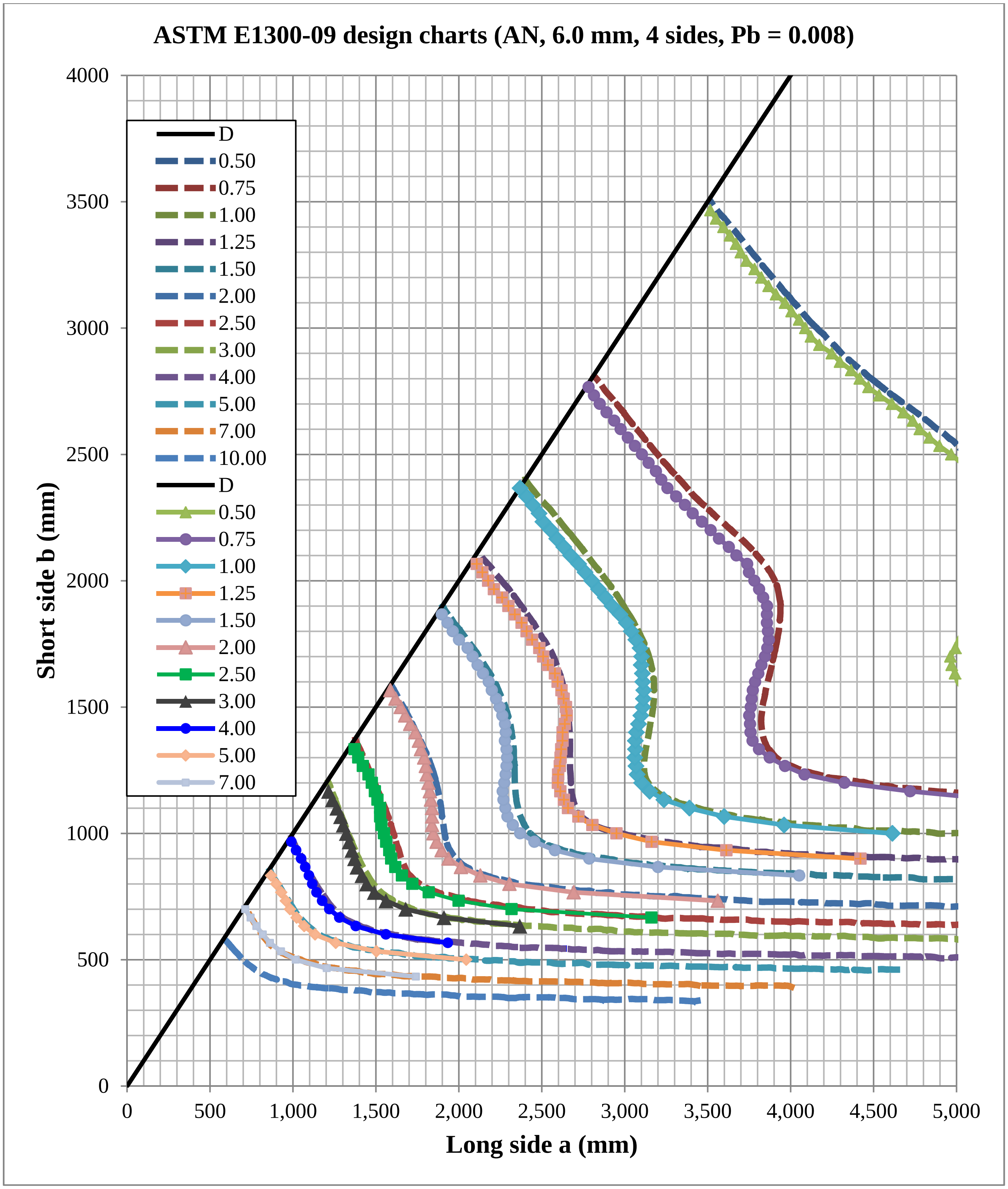
$$\mathrm{LR} \geq q \tag{25}$$

4 Design charts

Design charts generated by GLASS–BR 0.39 for a single lite of annealed glass, 4-side supported, and a target probability of breakage P_b = 8/1000. The software assumes a range of values for side a and finds the matching b–value that result in the target P_b.



Design charts generated by GLASS–BR 0.40 for a single lite of annealed glass, 4-side supported, and a target probability of breakage P_b = 8/1000. The software assumes a range of values for side b and finds the matching a–value that result in the target P_b.



5 BENCHMARK TESTS

5.1 Test T1

General Geometry			
Long side (*a*)		1600.00	mm
Short side (*b*)		1200.00	mm
Glazing type		Insulating glass unit (IG)	
Nominal thickness: lite-1		8.00	mm
Glass type (PVB laminate): lite-1		HS (heat strengthened)	
Nominal thickness: lite-2		8.00	mm
Glass type (PVB laminate): lite-2		HS (heat strengthened)	
Boundary Conditions		4 sides supported	
Response Type		Flexural	

Mechanical Properties			
Elastic modulus (*E*)		7.17E+07	kPa
Surface flaw parameter (*m*)		7.00E+00	
Surface flaw parameter (*k*)		2.86E-53	$N^{-7}m^{12}$

Target Probability of Breakage			
P_b-tolerable		8.00	/1000

Charge Weight & Standoff	
W (kg)	40.00
Explosive	TNT
TNT eq. factor	1.00
SD_x (m)	20.00
SD_y (m)	0.00
SD_z (m)	0.00

<u>Three–Second Duration equivalent design pressure:</u>

- Convert given explosive mass in equivalent mass of TNT: $W_{TNT} = 40 \times 1 = 40\,\text{kg}$
- Calculate slanted standoff distance: $SD = \sqrt{20^2 + 0^2 + 0^2} = 20\,\text{m}$
- q = 4.75 kPa

<u>Non–Factored Loads:</u>

NFL_1 = 3.5 kPa

NFL_2 = 3.5 kPa

Glass Type Factors:

GTF_1 = 1.8

GTF_2 = 1.8

True thicknesses:

h_1 = 7.42 mm

h_2 = 7.42 mm

Load Sharing Factors:

$$\mathrm{LSF}_1 = \frac{7.42^3 + 7.42^3}{7.42^3} = 2.0$$

$$\mathrm{LSF}_2 = \frac{7.42^3 + 7.42^3}{7.42^3} = 2.0$$

Load resistance:

$\mathrm{LR}_1 = 3.5 \times 1.8 \times 2.0 = 12.6\,\mathrm{kPa}$

$\mathrm{LR}_2 = 3.5 \times 1.8 \times 2.0 = 12.6\,\mathrm{kPa}$

$\mathrm{LR} = \min\{\mathrm{LR}_1, \mathrm{LR}_2\} = 12.6\,\mathrm{kPa}$

Design requirement:

$\mathrm{LR} \geq q$ :: 12.6 ≥ 4.75 kPa :: YES!

Probability of Glass Breakage

Aspect ratio: a/b = 1600/1200 = 1.333

Non–dimensional loads:

$$\hat{q}_1 = \frac{q(ab)^2}{Eh_1^4}\frac{1}{\mathrm{GTF}_1}\frac{1}{\mathrm{LSF}_1} = \frac{4.75 \times (1600 \times 1200)^2}{7.17 \times 10^7 \times 7.42^4} \times \frac{1}{1.8} \times \frac{1}{2.0} = 22.38$$

$$\hat{q}_2 = \frac{q(ab)^2}{Eh_2^4}\frac{1}{\mathrm{GTF}_2}\frac{1}{\mathrm{LSF}_2} = \frac{4.75 \times (1600 \times 1200)^2}{7.17 \times 10^7 \times 7.42^4} \times \frac{1}{1.8} \times \frac{1}{2.0} = 22.38$$

Stress Distribution Factors:

J_1 = 10.5

J_2 = 10.5

Probabilities of failure:

$$\text{LDF} = \left(\frac{t_d}{60}\right)^{\frac{m}{16}} = \left(\frac{3}{60}\right)^{\frac{7}{16}} = 0.2696$$

$$B_1 = \frac{k}{(ab)^{m-1}}\left(Eh_1^2\right)^m \exp\left[J_1\left(m, \hat{q}_1, \frac{a}{b}\right)\right]\text{LDF}$$

$$B_1 = \frac{2.86\times10^{-53}}{(1.6\times1.2)^6}\left(7.17\times10^{10}\times0.00742^2\right)^7 \exp(10.5)\times0.2696 = 8.349\times10^{-5}$$

$$B_2 = \frac{k}{(ab)^{m-1}}\left(Eh_2^2\right)^m \exp\left[J_2\left(m, \hat{q}_2, \frac{a}{b}\right)\right]\text{LDF}$$

$$B_2 = \frac{2.86\times10^{-53}}{(1.6\times1.2)^6}\left(7.17\times10^{10}\times0.00742^2\right)^7 \exp(10.5)\times0.2696 = 8.349\times10^{-5}$$

$$P_{b1} = 1-\exp\left[-B_1\right] = 1-\exp\left(-8.349\times10^{-5}\right) = 8.349\times10^{-5}$$

$$P_{b2} = 1-\exp\left[-B_2\right] = 1-\exp\left(-8.349\times10^{-5}\right) = 8.349\times10^{-5}$$

$$P_b = \max\left\{P_{b1}, P_{b2}\right\} = \max\left\{8.349\times10^{-5}, 8.349\times10^{-5}\right\} = 8.349\times10^{-5} = 0.08/1000$$

Design requirement:

$$P_b \le P_{b-tol} = 0.008 \;::\; 8.349\times10^{-5} \le 8\times10^{-3} \text{ YES!}$$

DESIGN METHODOLOGY "D2"

Stress Distribution Factors associated with P_{b-tol}:

$$J_{tol-1} = J\left(P_{b-tol}, h_1\right) = \ln\left[\ln\left(\frac{1}{1-P_{b-tol}}\right)\frac{(ab)^{m-1}}{k\left(Eh_1^2\right)^m}\left(\frac{60}{t_d}\right)^{\frac{m}{16}}\right]$$

$$J_{tol-1} = J\left(P_{b-tol}, h_1\right) = \ln\left[\ln\left(\frac{1}{1-0.008}\right)\frac{(1.6\times1.2)^6}{2.86\times10^{-53}\times\left(7.17\times10^{10}\times0.00742^2\right)^7}\left(\frac{60}{3}\right)^{\frac{7}{16}}\right]$$

$$J_{tol-1} = 15.07$$

$$J_{tol-2} = J\left(P_{b-tol}, h_2\right) = \ln\left[\ln\left(\frac{1}{1-P_{b-tol}}\right)\frac{(ab)^{m-1}}{k\left(Eh_2^2\right)^m}\left(\frac{60}{t_d}\right)^{\frac{m}{16}}\right]$$

$$J_{tol-2} = J\left(P_{b-tol}, h_2\right) = \ln\left[\ln\left(\frac{1}{1-0.008}\right)\frac{(1.6\times1.2)^6}{2.86\times10^{-53}\times\left(7.17\times10^{10}\times0.00742^2\right)^7}\left(\frac{60}{3}\right)^{\frac{7}{16}}\right]$$

$$J_{tol-2} = 15.07$$

Non–factored load:

a/b = 1600/1200 = 1.333

Fig. X3.1 → $\hat{q}_1\left(J_{tol-1}\right) = 52$

Fig. X3.1 → $\hat{q}_2\left(J_{tol-2}\right) = 52$

$$\text{NFL}_1 = \frac{q_1}{\text{GTF}_1\,\text{LSF}_1} = \hat{q}_1\frac{Eh_1^4}{(ab)^2} = 52\times\frac{7.17\times10^7\times.00742^4}{(1.6\times1.2)^2} = 3.067\text{ kPa}$$

$$\text{NFL}_2 = \frac{q_2}{\text{GTF}_2\,\text{LSF}_2} = \hat{q}_2\frac{Eh_2^4}{(ab)^2} = 52\times\frac{7.17\times10^7\times.00742^4}{(1.6\times1.2)^2} = 3.067\text{ kPa}$$

Load Resistance:

$$\text{LR}_1 = q_1 = \left(\text{NFL}_1\right)\left(\text{GTF}_1\right)\left(\text{LSF}_1\right) = 3.067\times1.8\times2.0 = 11.04$$

$$\text{LR}_2 = q_2 = \left(\text{NFL}_2\right)\left(\text{GTF}_2\right)\left(\text{LSF}_2\right) = 3.067\times1.8\times2.0 = 11.04$$

$$\text{LR} = \min\left\{\text{LR}_1, \text{LR}_2\right\} = \min\left\{11.04, 11.04\right\} = 11.04\text{ kPa}$$

Design requirement:

LR ≥ q :: 11.04 ≥ 4.75 kPa YES!

Summary:

Output T1 (ASTM E1300-09)			D1	D2
3-second duration equivalent pressure	**4.73**	kPa	4.75	-
Non-factored load (NFL1)	3.09	KPa	3.50	3.07
Glass type factor (GT1)	1.81		1.80	-
Load share factor (LS1)	2.00		2.00	-
Load resistance (LR1)	11.17	KPa	12.60	11.04
Non-factored load (NFL2)	3.09	KPa	3.50	3.07
Glass type factor (GT2)	1.81		1.80	-
Load share factor (LS2)	2.00		2.00	-
Load resistance (LR2)	11.17	KPa	12.60	11.04
Load resistance LR=min(LR1,LR2)	**11.17**	KPa	12.60	11.04
CAPACITY > DEMAND?	**YES**		YES	YES
Aspect ratio (a/b)	1.33		1.33	-
Load duration factor [(td/60)^(m/16)]	0.27		0.27	-
True thickness (h1)	7.42	mm	7.42	-
Nondimensional pressure (q1*)	22.23		22.38	-
Stress distribution factor (J1)	10.29		10.50	-
Probability of breakage (Pb1)	0.07	/1000	0.08	-
True thickness (h2)	7.42	mm	7.42	-
Nondimensional pressure (q2*)	22.23		22.38	-
Stress distribution factor (J2)	10.29		10.50	-
Probability of breakage (Pb2)	0.07	/1000	0.08	-
Probability of breakage Pb=max(Pb1,Pb2)	**0.07**	/1000	0.08	-
Pb < Pb-tolerable?	**YES**		YES	-

5.2 Test T2

General Geometry			
Long side (a)		1600.00	mm
Short side (b)		1200.00	mm
Glazing type		Monolithic-laminated (LG)	
Nominal thickness: lite-1		8.00	mm
Glass type (PVB laminate): lite-1		AN (annealed)	
Nominal thickness: lite-2		0.00	mm
Glass type (PVB laminate): lite-2		None	
Boundary Conditions		4 sides supported	
Response Type		Flexural	

Mechanical Properties			
Elastic modulus (E)		7.17E+07	kPa
Surface flaw parameter (m)		7.00E+00	
Surface flaw parameter (k)		2.86E-53	$N^{-7}m^{12}$

Target Probability of Breakage			
P_b-tolerable		8.00	/1000

Charge Weight & Standoff	
W (kg)	30.00
Explosive	TNT
TNT eq. factor	1.00
SD_x (m)	15.00
SD_y (m)	5.00
SD_z (m)	3.00

<u>Three–Second Duration equivalent design pressure:</u>

- Convert given explosive mass in equivalent mass of TNT: $W_{TNT} = 30 \times 1 = 40\,\text{kg}$
- Calculate slanted standoff distance: $SD = \sqrt{15^2 + 5^2 + 3^2} = 16.09\,\text{m}$
- q = 4.75 kPa

<u>Non–Factored Loads:</u>

NFL_1 = 3.5 kPa

NFL_2 = 0.0 kPa

Glass Type Factors:

GTF_1 = 1.0

GTF_2 = 0.0

True thicknesses:

h_1 = 7.42 mm

h_2 = 0.00 mm

Load Sharing Factors:

$$\mathrm{LSF}_1 = \frac{7.42^3 + 0.00^3}{7.42^3} = 1.0$$

$$\mathrm{LSF}_2 = 0.0$$

Load resistance:

$\mathrm{LR}_1 = 3.5 \times 1.0 \times 1.0 = 3.5\,\mathrm{kPa}$

$\mathrm{LR}_2 = 0.0\,\mathrm{kPa}$

$\mathrm{LR} = \mathrm{LR}_1 = 3.5\,\mathrm{kPa}$

Design requirement:

$\mathrm{LR} \geq q$ :: 3.50 ≥ 4.75 kPa :: NO!

Probability of Glass Breakage

Aspect ratio: a/b = 1600/1200 = 1.333

Non–dimensional loads:

$$\hat{q}_1 = \frac{q(ab)^2}{Eh_1^4}\frac{1}{\mathrm{GTF}_1}\frac{1}{\mathrm{LSF}_1} = \frac{4.75 \times (1600 \times 1200)^2}{7.17 \times 10^7 \times 7.42^4} \times \frac{1}{1.0} \times \frac{1}{1.0} = 80.57$$

$$\hat{q}_2 = 0.0$$

Stress Distribution Factors:

J_1 = 17.0

J_2 = 0.0

Probabilities of failure:

$$\text{LDF} = \left(\frac{t_d}{60}\right)^{\frac{m}{16}} = \left(\frac{3}{60}\right)^{\frac{7}{16}} = 0.2696$$

$$B_1 = \frac{k}{(ab)^{m-1}}\left(Eh_1^2\right)^m \exp\left[J_1\left(m, \hat{q}_1, \frac{a}{b}\right)\right]\text{LDF}$$

$$B_1 = \frac{2.86\times10^{-53}}{(1.6\times1.2)^6}\left(7.17\times10^{10}\times0.00742^2\right)^7 \exp(17.0)\times0.2696 = 5.554\times10^{-2}$$

$$B_2 = \frac{k}{(ab)^{m-1}}\left(Eh_2^2\right)^m \exp\left[J_2\left(m, \hat{q}_2, \frac{a}{b}\right)\right]\text{LDF}$$

$$B_2 = 0.0$$

$$P_{b1} = 1-\exp\left[-B_1\right] = 1-\exp\left(-5.554\times10^{-2}\right) = 5.403\times10^{-2}$$

$$P_{b2} = 0.0$$

$$P_b = P_{b1} = 5.403\times10^{-2} = 54.03/1000$$

Design requirement:

$$P_b \le P_{b-tol} = 0.008 \ :: \ 5.403\times10^{-2} \le 8\times10^{-3} \ \text{ NO!}$$

DESIGN METHODOLOGY “D2”

Stress Distribution Factors associated with P_{b-tol}:

$$J_{tol-1} = J\left(P_{b-tol}, h_1\right) = \ln\left[\ln\left(\frac{1}{1-P_{b-tol}}\right)\frac{(ab)^{m-1}}{k\left(Eh_1^2\right)^m}\left(\frac{60}{t_d}\right)^{\frac{m}{16}}\right]$$

$$J_{tol-1} = J\left(P_{b-tol}, h_1\right) = \ln\left[\ln\left(\frac{1}{1-0.008}\right)\frac{(1.6\times1.2)^6}{2.86\times10^{-53}\times\left(7.17\times10^{10}\times0.00742^2\right)^7}\left(\frac{60}{3}\right)^{\frac{7}{16}}\right]$$

$$J_{tol-1} = 15.07$$

$$J_{tol-2} = J\left(P_{b-tol}, h_2\right) = \ln\left[\ln\left(\frac{1}{1-P_{b-tol}}\right)\frac{(ab)^{m-1}}{k\left(Eh_2^2\right)^m}\left(\frac{60}{t_d}\right)^{\frac{m}{16}}\right]$$

$$J_{tol-2} = J\left(P_{b-tol}, h_2\right) = 0.0$$

Non–factored load:

a/b = 1600/1200 = 1.333

Fig. X3.1 → $\hat{q}_1\left(J_{tol-1}\right) = 52$

Fig. X3.1 → $\hat{q}_2\left(J_{tol-2}\right) = 0.0$

$$\mathrm{NFL}_1 = \frac{q_1}{\mathrm{GTF}_1\,\mathrm{LSF}_1} = \hat{q}_1\frac{Eh_1^4}{(ab)^2} = 52\times\frac{7.17\times10^7\times.00742^4}{(1.6\times1.2)^2} = 3.067\ \mathrm{kPa}$$

$\mathrm{NFL}_2 = 0.0$ kPa

Load Resistance:

$\mathrm{LR}_1 = q_1 = (\mathrm{NFL}_1)(\mathrm{GTF}_1)(\mathrm{LSF}_1) = 3.067\times1.0\times1.0 = 3.067$

$\mathrm{LR}_2 = 0.0$

LR = $\mathrm{LR}_1 = 3.067$ kPa

Design requirement:

LR ≥ q :: 3.07 ≥ 4.75 kPa YES!

Summary:

Output T2 (ASTM E1300-09)			D1	D2
3-second duration equivalent pressure	**4.72**	kPa	4.75	-
Non-factored load (NFL1)	3.09	KPa	3.50	3.07
Glass type factor (GT1)	1.00		1.00	-
Load share factor (LS1)	1.00		1.00	-
Load resistance (LR1)	3.09	KPa	3.50	3.07
Non-factored load (NFL2)	0.00	KPa	0.00	0.00
Glass type factor (GT2)	0.00		0.00	-
Load share factor (LS2)	0.00		0.00	-
Load resistance (LR2)	0.00	KPa	0.00	0.00
Load resistance LR=min(LR1,LR2)	**3.09**	KPa	3.50	3.07
CAPACITY > DEMAND?	**NO**		NO	NO
Aspect ratio (a/b)	1.33		1.33	-
Load duration factor [(td/60)^(m/16)]	0.27		0.27	-
True thickness (h1)	7.42	mm	7.42	-
Nondimensional pressure (q1*)	80.02		80.57	-
Stress distribution factor (J1)	17.10		17.00	-
Probability of breakage (Pb1)	59.62	/1000	54.03	-
True thickness (h2)	0.00	mm	0.00	-
Nondimensional pressure (q2*)	0.00		0.00	-
Stress distribution factor (J2)	0.00		0.00	-
Probability of breakage (Pb2)	0.00	/1000	0.00	-
Probability of breakage Pb=max(Pb1,Pb2)	**59.62**	/1000	54.03	-
Pb < Pb-tolerable?	**NO**		NO	-

5.3 Test T3 (based on ASTM E1300-09 – Cl. X3.3.1)

General Geometry			
Long side (a)		1500.00	mm
Short side (b)		1200.00	mm
Glazing type		Monolithic-laminated (LG)	
Nominal thickness: lite-1		6.00	mm
Glass type (PVB laminate): lite-1		AN (annealed)	
Nominal thickness: lite-2		0.00	mm
Glass type (PVB laminate): lite-2		None	
Boundary Conditions		4 sides supported	
Response Type		Flexural	

Mechanical Properties			
Elastic modulus (E)		7.17E+07	kPa
Surface flaw parameter (m)		7.00E+00	
Surface flaw parameter (k)		2.86E-53	$N^{-7}m^{12}$

Target Probability of Breakage			
P_b-tolerable		8.00	/1000

Charge Weight & Standoff	
W (kg)	42.00
Explosive	TNT
TNT eq. factor	1.00
SD_x (m)	41.00
SD_y (m)	0.00
SD_z (m)	3.00

<u>Three–Second Duration equivalent design pressure:</u>

- Convert given explosive mass in equivalent mass of TNT: $W_{TNT} = 42 \times 1 = 42\,\text{kg}$
- Calculate slanted standoff distance: $SD = \sqrt{41^2 + 0^2 + 3^2} = 41.11\,\text{m}$
- q = 2.20 kPa

<u>Non–Factored Loads:</u>

NFL_1 = 2.50 kPa

NFL_2 = 0.0 kPa

Glass Type Factors:

$GTF_1 = 1.0$

$GTF_2 = 0.0$

True thicknesses:

$h_1 = 5.56$ mm

$h_2 = 0.00$ mm

Load Sharing Factors:

$$\mathrm{LSF}_1 = \frac{5.56^3 + 0.00^3}{5.56^3} = 1.0$$

$$\mathrm{LSF}_2 = 0.0$$

Load resistance:

$$\mathrm{LR}_1 = 2.50 \times 1.0 \times 1.0 = 2.50\,\mathrm{kPa}$$

$$\mathrm{LR}_2 = 0.0\,\mathrm{kPa}$$

$$\mathrm{LR} = \mathrm{LR}_1 = 2.50\,\mathrm{kPa}$$

Design requirement:

$\mathrm{LR} \geq q$ :: 2.50 ≥ 2.20 kPa :: YES!

Probability of Glass Breakage:

Aspect ratio: a/b = 1500/1200 = 1.25

Non–dimensional loads:

$$\hat{q}_1 = \frac{q(ab)^2}{Eh_1^4}\frac{1}{\mathrm{GTF}_1}\frac{1}{\mathrm{LSF}_1} = \frac{2.20 \times (1500 \times 1200)^2}{7.17 \times 10^7 \times 5.56^4} \times \frac{1}{1.0} \times \frac{1}{1.0} = 104.0$$

$$\hat{q}_2 = 0.0$$

Stress Distribution Factors:

$J_1 = 18.2$

$J_2 = 0.0$

Probabilities of failure:

$$\text{LDF} = \left(\frac{t_d}{60}\right)^{\frac{m}{16}} = \left(\frac{3}{60}\right)^{\frac{7}{16}} = 0.2696$$

$$B_1 = \frac{k}{(ab)^{m-1}}\left(Eh_1^2\right)^m \exp\left[J_1\left(m, \hat{q}_1, \frac{a}{b}\right)\right]\text{LDF}$$

$$B_1 = \frac{2.86\times10^{-53}}{(1.5\times1.2)^6}\left(7.17\times10^{10}\times0.00556^2\right)^7 \exp(18.2)\times0.2696 = 4.779\times10^{-3}$$

$$B_2 = \frac{k}{(ab)^{m-1}}\left(Eh_2^2\right)^m \exp\left[J_2\left(m, \hat{q}_2, \frac{a}{b}\right)\right]\text{LDF}$$

$$B_2 = 0.0$$

$$P_{b1} = 1-\exp\left[-B_1\right] = 1-\exp\left(-4.779\times10^{-3}\right) = 4.767\times10^{-3}$$

$$P_{b2} = 0.0$$

$$P_b = P_{b1} = 4.767\times10^{-3} = 4.767/1000$$

LDF = 1.0 → B_1 = 1.772% → P_b = 1.757%

Design requirement:

$$P_b \le P_{b-tol} = 0.008 \ :: \ 4.767\times10^{-3} \le 8\times10^{-3} \ \text{ YES!}$$

DESIGN METHODOLOGY "D2"

Stress Distribution Factors associated with P_{b-tol}:

$$J_{tol-1} = J\left(P_{b-tol}, h_1\right) = \ln\left[\ln\left(\frac{1}{1-P_{b-tol}}\right)\frac{(ab)^{m-1}}{k\left(Eh_1^2\right)^m}\left(\frac{60}{t_d}\right)^{\frac{m}{16}}\right]$$

$$J_{tol-1} = J\left(P_{b-tol}, h_1\right) = \ln\left[\ln\left(\frac{1}{1-0.008}\right)\frac{(1.5\times1.2)^6}{2.86\times10^{-53}\times\left(7.17\times10^{10}\times0.00556^2\right)^7}\left(\frac{60}{3}\right)^{\frac{7}{16}}\right]$$

$$J_{tol-1} = 18.72$$

$$J_{tol-2} = J\left(P_{b-tol}, h_2\right) = \ln\left[\ln\left(\frac{1}{1-P_{b-tol}}\right)\frac{(ab)^{m-1}}{k\left(Eh_2^2\right)^m}\left(\frac{60}{t_d}\right)^{\frac{m}{16}}\right]$$

$$J_{tol-2} = J\left(P_{b-tol}, h_2\right) = 0.0$$

Non–factored load:

a/b = 1500/1200 = 1.25

Fig. X3.1 → $\hat{q}_1\left(J_{tol-1}\right) = 116.3$

Fig. X3.1 → $\hat{q}_2\left(J_{tol-2}\right) = 0.0$

$$\mathrm{NFL}_1 = \frac{q_1}{\mathrm{GTF}_1\,\mathrm{LSF}_1} = \hat{q}_1\,\frac{Eh_1^4}{(ab)^2} = 116.3 \times \frac{7.17\times 10^7 \times 0.00556^4}{(1.5\times 1.2)^2} = 2.531\ \mathrm{kPa}$$

$\mathrm{NFL}_2 = 0.0\ \mathrm{kPa}$

Load Resistance:

$\mathrm{LR}_1 = q_1 = (\mathrm{NFL}_1)(\mathrm{GTF}_1)(\mathrm{LSF}_1) = 2.531\times 1.0 \times 1.0 = 2.531\,\mathrm{kPa}$

$\mathrm{LR}_2 = 0.0\,\mathrm{kPa}$

LR = $\mathrm{LR}_1 = 2.531\ \mathrm{kPa}$

Design requirement:

LR ≥ q :: 2.53 ≥ 2.20 kPa YES!

Summary:

Output T3 (ASTM E1300-09)			D1	D2
3-second duration equivalent pressure	**2.20**	kPa	2.20	-
Non-factored load (NFL1)	2.46	KPa	2.50	2.53
Glass type factor (GT1)	1.00		1.00	-
Load share factor (LS1)	1.00		1.00	-
Load resistance (LR1)	2.46	KPa	2.50	2.53
Non-factored load (NFL2)	0.00	KPa	0.00	0.00
Glass type factor (GT2)	0.00		0.00	-
Load share factor (LS2)	0.00		0.00	-
Load resistance (LR2)	0.00	KPa	0.00	0.00
Load resistance LR=min(LR1,LR2)	**2.46**	KPa	2.50	2.53
CAPACITY > DEMAND?	**YES**		YES	YES
Aspect ratio (a/b)	1.25		1.25	-
Load duration factor [(td/60)^(m/16)]	0.27		0.27	-
True thickness (h1)	5.56	mm	5.56	-
Nondimensional pressure (q1*)	104.17		104.00	-
Stress distribution factor (J1)	18.22		18.20	-
Probability of breakage (Pb1)	4.85	/1000	4.77	-
True thickness (h2)	0.00	mm	0.00	-
Nondimensional pressure (q2*)	0.00		0.00	-
Stress distribution factor (J2)	0.00		0.00	-
Probability of breakage (Pb2)	0.00	/1000	0.00	-
Probability of breakage Pb=max(Pb1,Pb2)	**4.85**	/1000	4.77	-
Pb < Pb-tolerable?	**YES**		YES	-

6 NOTATION

a	=	Long side (mm)
b	=	Short side (mm)
E	=	Glass Young's modulus (kPa)
GTF	=	Glass Type Factor
h	=	True (minimum) glass thickness (mm)
IGU	=	Insulating Glass Unit
J	=	Stress Distribution Factor (SDF)
J_{tol}	=	Stress Distribution Factor associated with P_{b-tol}
k	=	First flaw parameter ($N^{-7}m^{12}$)
LDF	=	Load Duration Factor
LSF	=	Load Sharing Factor
LR	=	Load Resistance (kPa)
m	=	Second flaw parameter
NFL	=	Non-Factored Load
P_b	=	Probability of breakage
P_{b-tol}	=	Tolerable probability of breakage (e.g. 0.008)
SDF	=	Stress Distribution Factor (also J)
TNT_{eq}	=	TNT equivalency factor
TSD	=	Three Second Duration equivalent pressure (also q)
q	=	Three Second Duration equivalent pressure (also SDF, kPa)
$\hat{q}$	=	Non–dimensional pressure
SD	=	Slanted standoff distance (m)
SD_x	=	Standoff distance – x projection (m)
SD_y	=	Standoff distance – y projection (m)
SD_z	=	Standoff distance – z projection (m)
W_{ex}	=	Explosive charge mass (kg)
W_{TNT}	=	TNT charge mass (kg)

7 References

ASTM, 2009a. *Standard Practice for Determining Load Resistance of Glass in Buildings. ASTM Standard E1300-09a*, West Conshohocken, PA: American Society for Testing and Materials (ASTM). Available at: http://compass.astm.org/EDIT/html_historical.cgi?E1300+09a.

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