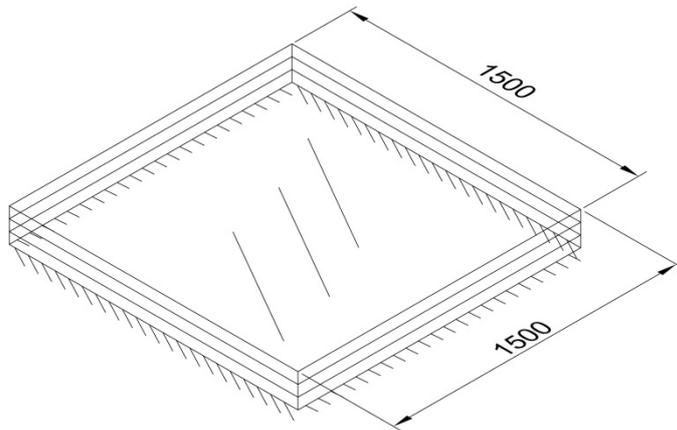


Preview of Structural Use of Glass in Buildings Second Edition
By Chris O'Regan BEng(Hons) CEng MStructE

Worked example for floor plate design

A glass floor plate is to be installed that sits over a basement. The support is via a steel frame with a 1.5m x 1.5m grillage of beams. This frame provides a continuous support and the following analysis and design of the glass floor plate provisionally assumes it to be infinitely stiff. The following calculation determines the thickness of the glass required for the floor plate.



The below floor loadings are typical for domestic use and should be used for design:

Characteristic variable action $q_k = 1.5\text{kN/m}^2$
 Characteristic point action $Q_k = 3.0\text{kN}$

The glass will not be sandblasted and will be enamelled on the wearing side. This will not impact on the design of the glass as the enamelling is on the compression side of the floor plate.

The glass is to be made up of three layers of glass laminated with PVB, It is assumed that the top sheet will be toughened and not included in the stress calculations although will be considered for deflection. To provide the most effective post breakage behaviour the lower two sheets will be heat strengthened.

Two action durations apply: permanent and short.

Permanent action condition

Determine design strength of glass using Appendix C.

$$f_{g;d} = \frac{k_{mod}k_{sp}f_{g;k}}{\gamma_{M:A}} + \frac{k_v(f_{b;k} - f_{g;k})}{\gamma_{M:v}}$$

For load duration > 50 years, $k_{mod} = 0.29$

$k_{mod} = 0.29$, $k_{sp} = 1.0$, $f_{g;k} = 45\text{ N/mm}^2$, $f_{b;k} = 70\text{ N/mm}^2$, $k_v = 1.0$, $\gamma_{M:A} = 1.6$ and $\gamma_{M:v} = 1.2$.

$$f_{g;d} = \frac{0.29 \times 1.0 \times 45\text{ N/mm}^2}{1.6} + \frac{1.0(70\text{ N/mm}^2 - 45\text{ N/mm}^2)}{1.2} = 29\text{ N/mm}^2$$

Variable action condition i.e. short duration load

For load duration of 5 hours, for pedestrian action; $k_{mod} = 0.60$

$$\therefore f_{g;d} = \frac{0.60 \times 1.0 \times 45\text{ N/mm}^2}{1.6} + \frac{1.0(70\text{ N/mm}^2 - 45\text{ N/mm}^2)}{1.2} = 37.7\text{ N/mm}^2$$

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Determine the effective thickness of the glass required based on design strength

Try two 12mm thick plies and one 12mm thick sacrificial ply. The laminate is a PVB based material and is 0.76mm thick.

In order to calculate the effective thickness of the glass pane, the shear interaction between the plies of the laminated glass via the PVB interlayer must be accounted for.

The simplified method of determining stress of glass within each ply is as follows.

The effective thickness of the glass when considering deflection due to bending is:

$$h_{ef,w} = \sqrt[3]{\sum_k h_k^3 + 12\omega \left(\sum_i h_k h_{m,k}^2 \right)}$$

where:

h_k is the thickness of each ply

$h_{m,k}$ is the distance between the middle of the ply to the centre of the laminated glass pane.

When calculating stress the equivalent thickness is calculated from:

$$h_{ef,\sigma;j} = \sqrt{\frac{h_{ef,w}^3}{h_j + 2\omega h_{m;j}}}$$

where:

h_j is the thickness of each ply

$h_{m;j}$ is the distance between the middle of the ply to the centre of the laminated glass pane.

Assuming a value of 0.1 for ω when considering variable actions and '0' when assessing effects due to permanent actions, two effective thicknesses need to be calculated.

Effective thickness in permanent action condition

The effective thickness of the laminated glass with respect to permanent action is as follows:

$$h_{ef,w} = \sqrt[3]{12^3 \text{ mm} + 12^3 \text{ mm}} = 15.1 \text{ mm}$$

Note that the variable ω equates to '0' hence it is not included in the calculation. Additionally the toughened glass top ply is not included when determining the overall depth of the glass as it is considered to be sacrificial.

Effective thickness in Variable Action Condition

The effective thickness of the laminated glass with respect to variable action is as follows:

$$h_{ef,w} = \sqrt[3]{\frac{12^3 \text{ mm} + 12^3 \text{ mm} + 12 \times 0.1 \times (12 \text{ mm} \times 6.4^2 \text{ mm})}{6.4^2 \text{ mm} + 12 \text{ mm} \times 6.4^2 \text{ mm}}} = 16.7 \text{ mm}$$

This is the effective thickness of the laminated glass that is to be used for deflection calculations.

The effective thickness of the laminated glass for bending stress is as follows:

$$h_{ef,\sigma;j} = \sqrt{\frac{16.7^3 \text{ mm}}{12 \text{ mm} + 2 \times 0.1 \times 6.4 \text{ mm}}} = 18.7 \text{ mm}$$

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Note how the thickness has increased from 15.1mm to 16.7mm due to the inclusion of shear interaction within the PVB based interlayer, which is then increased to 18.7mm when calculating stress

Bending stress check

There are two action conditions to check for: permanent and variable (short). With respect to the permanent condition, the following applies:

Permanent Actions due to self-weight = $0.036\text{m} \times 25\text{kN/m}^3 = 0.9\text{kN/m}^2$

(Note this includes the 12mm thick toughened glass top ply which is not included when determining the effective thickness of the glass.)

Partial factor for permanent action $\gamma_g=1.35$

$$UDL_{ult} = 0.9\text{kN/m}^2 \times \gamma_g = 0.9\text{kN/m}^2 \times 1.35 = 1.22\text{kN/m}^2$$

The applied bending stress to the plate during the permanent condition is defined in Table 11.4 of Roark's Formulas for Stress and Strain – 8th Edition as:

$$\sigma_{max} = \frac{\beta qb^2}{h_{ef,w}^2}, \beta = 0.287$$

The β variable is dependent upon the ratio of geometry of the plate. In this instance the ratio of the dimensions of the plate is 1; therefore $\beta = 0.287$

$$\therefore \sigma_{max} = \frac{0.287 \times 1.22\text{kN/m}^2 \times 1.5^2\text{m}}{0.0187^2\text{m}} = 2252\text{kN/m}^2$$

$$2.3\text{N/mm}^2 < 29\text{N/mm}^2 \therefore \text{OK}$$

The applied bending stress to the plate during the variable action condition is:

$$1.22\text{kN/m}^2 + 1.5 \text{ kN/m}^2 \times \gamma_q = 1.22\text{kN/m}^2 + 1.5 \text{ kN/m}^2 \times 1.5 = 3.47\text{kN/m}^2$$

There are two effects to consider for the variable action condition: that of the UDL and the point load.

UDL

$$\sigma_{max} = \frac{0.287 \times 3.47\text{kN/m}^2 \times 1.5^2\text{m}}{0.0187^2\text{m}} = 6408\text{kN/m}^2$$

$$6.4\text{N/mm}^2 < 37.7\text{N/mm}^2 \therefore \text{OK}$$

Concentrated point action

The area over which the action is applied is $50\text{mm} \times 50\text{mm} = 2500\text{mm}^2$

$$\therefore \text{equivalent circle area radius } r_0=r'_0 \text{ if } r_0 \geq 0.5t \therefore r'_0 = \sqrt{\frac{2500\text{mm}^2}{\pi}} = 28.2\text{mm}$$

Bending stress at point of concentrated load:

$$\sigma = \frac{3W}{2\pi h_{ef;\sigma;j}^2} \left((1 + \nu) \ln \frac{2b}{\pi r'_0} + \beta \right)$$

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Where:

W is the design concentrated point action

ν is Poisson's Ratio

β is a variable that is dependent upon the ratio of geometry of the plate. See Table 11.4 of Roark's Formulas for Stress and Strain – 8th Edition.

In this instance the ratio of the dimensions of the plate equate to 1, therefore $\beta=0.435$

Partial factor for variable concentrated action $\gamma_0=1.5$

$$\therefore \sigma_{\text{point load}} = \frac{3 \times 3000\text{N} \times 1.5}{2 \times 18.7^2\text{mm}} \left[(1 + 0.22) \ln \frac{2 \times 1500\text{mm}}{\pi \times 28.2\text{mm}} + 0.435 \right] = 29.1\text{N/mm}^2$$

$$29.1\text{N/mm}^2 < 37.7\text{N/mm}^2 \therefore \text{OK}$$

Deflection check

It is safe to assume all three panels of glass participate in restricting deflection

Equivalent thickness of 3 layers is as follows:

$$h_{\text{ef},w} = \sqrt[3]{\frac{12^3\text{mm} + 12^3\text{mm} + 12^3\text{mm} + 12 \times 0.1 \times (12\text{mm} \times 12.8^2\text{mm} + 12\text{mm} \times 0\text{mm} + 12.8^2\text{mm} + 12\text{mm} \times 12.8^2\text{mm})}{12}} = 21.5\text{mm}$$

$$\text{Equivalent I value} = \frac{1500\text{mm} \times 21.5^3\text{mm}^3}{12} = 1242297\text{mm}^4$$

Taking the point load as the worst case condition:

Serviceability state deflection =

$$\frac{3000\text{N} \times 1500^3\text{mm}^3}{48 \times 70000\text{N/mm}^2 \times 1242297\text{mm}^4} = 2.4\text{mm}$$

Assuming a span/depth ratio of 250, the maximum allowable deflection is 6mm > 2.4mm therefore the floor plate passes both serviceability and strength checks.

Post-failure check

As all three sheets of glass could fail the only truly reliable test for the proposed design is to undergo physical testing of the design to confirm its suitability.

Some schools of thought suggest a design method where one sheet is assumed to remain intact. This can offer some measure of comfort but does not cover the case where all three sheets are broken. This approach is illustrated below.

Two action durations apply: permanent and short.

Permanent action condition

The strength of the glass is the same for the intact floor plate.

Bending stress check

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In the post-failure condition there remain the two action conditions to check for: permanent and variable (short). With respect to the permanent condition, the following applies:

Actions are similar to intact condition i.e. 0.9 kN/m²

Partial factor for permanent action $\gamma_g=1.0$ due to accidental condition

$$UDL_{ult} = 0.9\text{kN/m}^2 \times \gamma_g = 0.9\text{kN/m}^2 \times 1.00 = 0.9\text{kN/m}^2$$

When taking into account the two way spanning action of the floor plate, the applied bending stress to the plate during the permanent condition is:

$$\sigma_{\max} = \frac{\beta q b^2}{h_{\text{ef:w}}^2}, \beta = 0.287$$

$$\therefore \sigma_{\max} = \frac{0.287 \times 0.9\text{kN/m}^2 \times 1.5^2\text{m}}{0.012^2\text{m}} = 4036\text{kN/m}^2$$

$$4.0\text{N/mm}^2 < 29.0\text{N/mm}^2 \therefore \text{OK}$$

The applied bending stress to the plate during the variable action, short duration condition is:

Partial factor for variable action $\gamma_q=1.0$ due to accidental condition

$$UDL_{ult} = 0.9\text{kN/m}^2 + 1.5\text{kN/m}^2 \times \gamma_q = 0.9\text{kN/m}^2 + 1.5\text{kN/m}^2 \times 1.0 = 2.4\text{kN/m}^2$$

There are two effects to consider for the variable action condition: that of the UDL and point load.

UDL

$$\sigma_{\max} = \frac{0.287 \times 2.4\text{kN/m}^2 \times 1.5^2\text{m}}{0.012^2\text{m}} = 10763\text{kN/m}^2$$

$$10.8\text{N/mm}^2 < 37.7\text{N/mm}^2 \therefore \text{OK}$$

Point load check

Although this is an accidental condition, the point load check still applies.

Partial factor for variable concentrated action $\gamma_q=1.0$

$$\sigma_{\text{concentrated action}} = \frac{3 \times 3000\text{N} \times 1.0}{2 \times \pi \times 12^2\text{mm}} \left[(1 + 0.22) \ln \frac{2 \times 1500\text{mm}}{\pi \times 28.2\text{mm}} + 0.435 \right] = 47.1\text{N/mm}^2$$

$$47.1\text{N/mm}^2 > 37.7\text{N/mm}^2 \therefore \text{fails}$$

If the two bottom sheets remain as 14 mm and the top sheet is dropped to 8mm then the overall thickness will remain the same and the stress calculated above will reduce to 34.6N/mm², which is within the allowable design bending stress.

No deflection check required as it is a post-failure condition.

The overall thickness of the glass is 37.5mm, which correlates closely to the span/depth ratio of 40.