Web Application For Analysis and Monitoring of Flat Thin Rectangular Glass Panel in Buildings Subjected to Wind and Seismic Forces

by

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Web Application For Analysis and Monitoring of Flat Thin Rectangular Glass Panel in Buildings Subjected to Wind and Seismic Forces

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ABSTRACT

Huge damages and loss of lives due to failure of glass panels and façade structures in buildings reported during past disasters such as the 1983 Mid-Japan Sea Earthquake and glass curtain façade failures due to 1994 Typhoon in Wan Chai district of Hong Kong suggest that there is a significant difference between available research literature related to structural mechanics, codes available on glass failure behavior and that with the safe structural design, mitigation practices actually implemented by modern construction firms and industries using significant structural glass components in buildings especially in newly emerging cities of India. This study presents a web application that simulates the behavior of glass plates towards two independent loading events: wind pressure acting transversely on the plates and seismic excitations deforming the in-plane glass frames leading to stress concentration patterns around plates. The App starts by prompting the user to input site-specific, plate geometry, building type and class, terrain, location-specific parameters. The framework of the application is designed in three stages. Stage-I uses computational GPS algorithms to determine Basic wind speed of the location based on wind zone map of India, combines analytical procedures in IS 875 Part III and Indian draft codes to formulate SNT(Standard Nominal Thickness) of glass plates and net design wind pressure acting transversely on them. In stage II, Deflection and bending behavior are investigated and relevant computations are performed. Mesh-generation procedures and Finite Element Method are implemented and coded by authors to solve the fourth order PDE of classical plate deflection and bending equation with relevant boundary conditions. And in stage III of analysis, buckling of glass panels due to in-plane seismic excitations and calculations for drift ratios are done adding the functionality of the app. The web application generates deflection contours, compares software results with analytical and code provisions and finally sends to the user, an output report of performance of glass component. Model calculations spanning over all three stages of analysis for different buildings’ glass plates in two cities of India are presented to demonstrate complete functionality.

Keywords: web application, wind pressures, earthquake force, buckling
1. INTRODUCTION

Glass plates are widely used as glazing window panels, façade structures, staircases and curtain walling in modern buildings as it has a unique quality of transparency and acceptable strength. Structurally it is a brittle material unlike conventional building materials like steel, aluminum, concrete etc. It is weak in tension due to its non-crystalline molecular configuration. It is for the same reason that glass panels used in old buildings were solely for architectural purposes. In modern era, we can witness huge surge in usage of glass elements for both non-structural and structural purposes due to its evident aesthetic and lighting properties. The causes of breakage of glass can be due to excessive deflection due to transverse loads, high in-plane deformation leading to excessive compressive stresses, buckling problems leading to surface damages etc. Due to advent of Information Technology, we do have numerous programs and software packages to achieve this goal, but inherent complexity, lack of durable platforms on which these programs run etc. make the quick and reliable monitoring of performance of glass elements tough for on-site engineers, consultants and other stakeholders. The work in this research paper presents the development of a UI based web application created by authors to analyze the performance of glass panels installed in buildings across Indian cities. Initial sections of the study highlight necessary and relevant literature review of the structural properties and behavior of glass panels used in buildings, procedures to calculate design wind and Earthquake forces acting on them in both out-of-plane and in-plane directions, analytical procedures to compute transverse deflections of glass plates and in-plane deformability of glass plates enclosed within the window frames. Further, the research paper emphasizes on the workflow and generation of the web application, core concepts on which its functionalities are based and a sample illustration of its working.

2. CALCULATION OF DESIGN WIND PRESSURE AND EQUIVALENT LATERAL SEISMIC FORCE ON GLASS PLATES

2.1 Design Wind Pressure

Wind zonal map of India according to IS 875, Part III (1987) gives the basic wind speed ($V_b$) as applicable at 10 m height above mean ground level for different zones of the country. It includes both the mean and the fluctuating components of the turbulent wind. Further, the basic wind speed shall be modified to include the following effects to get design wind speed, $V_z$ at any height, $z$ for the chosen structure: (a) Risk level, (b) Terrain roughness and height of structure, (c) Local topography, and (d) Importance factor for the cyclonic region. It can be mathematically expressed as follows:

$$V_z = V_b \cdot K_1 \cdot K_2 \cdot K_3 \cdot K_4$$

$V_z =$ Design wind speed at any height $z$ in m/s

$K_1 =$Probability factor (depends on mean probable design life of structure, Clause 5.3.1)

$K_2 =$obtain design wind speed variation with height in different terrains, Clause 5.3.2.2

$K_3 =$ Topography factor (takes account of the general level of site above sea level)

$K_4 = 1.30$ for post-cyclone importance, 1.15 for industrial structures, 1 otherwise
Further, the wind pressure at any height, \( z \) above mean ground level shall be obtained by assuming mass density of air as 1.20 kg/m\(^3\) which varies temperature and pressure.

\[
p_z = 0.6 \, \nu_z^2
\]

\( p_z \) = wind pressure in N/m\(^2\) at height \( z \) and,
\( \nu_z \) = design wind speed in m/s, the coefficient 0.6 for Indian weather conditions

The net design wind pressure \( p_d \) can be obtained as,

\[
p_d = p_z \cdot K_d \cdot K_a \cdot K_c
\]

\( K_d \) = wind directionality factor
\( K_a \) = area averaging factor
\( K_c \) = combination factor

2.2 Equivalent Static Lateral Force on glass panels due to Earthquake

Design seismic force, \( F_p \), on the non-structural element shall be calculated using the following expression as in IS 1893 (part 1) 2002:

\[
F_p = \frac{Z}{2} \left( 1 + \frac{x}{h} \right) a_p R_p W_p
\]

Where, \( Z = \) zone factor given in Table 2 of IS 1893 (part 1) 2002
\( x = \) height of point of attachment of glass plate above foundation
\( h = \) height of structure
\( a_p = \) component amplification factor given in Tables 2 and 3
\( R_p = \) component response modification factor
\( W_p = \) Weight of glass panel

Glazing systems are considered as deformation sensitive non-structural components as discussed in this design code. In choosing \( a_p \) and \( R_p \) values, it is expected that component will behave as either flexible (\( a_p = 2.5 \)) or rigid (\( a_p = 1.0 \)) body. In general, values of \( R_p \) are taken as 1.5, 2.5 and 3.5 for low, limited and high deformable structures, respectively.

3. DEFLECTION ANALYSIS OF FLAT RECTANGULAR GLASS PLATES DUE TO TRANSVERSE LOADING

Deflection affects the joint gaskets, sealants and supporting frames leading to high probability of failure against fatigue loading. Thin plate theory (Kirchhoff-Love model) is assumed while computing deflection behavior of the flat rectangular plates. Assumptions including plane stress conditions and planarity of middle surface of plate being maintained are made. With these small deflection assumptions and the boundary conditions, the deflection of the plate, \( w \), can be calculated.
Using equilibrium equations for small-displacement theory of flat plates and generalized boundary conditions equations, proper substitutions give the classic plate bending equation for thin, isotropic plate with pressure loading:

$$\nabla^2(D\nabla^2w) = -p$$  \hspace{1cm} (5)

Where $D$ is the flexural rigidity of plate given by:

$$D = \frac{Eh^3}{12(1-\nu^2)}$$  \hspace{1cm} (6)

And $E$ is the modulus of elasticity, $\nu$ is Poisson’s ratio, $h$ is the plate thickness. The transverse deflection of the plate is $w$ and $p$ is the pressure load.

### 3.1 Rectangular glass panels simply-supported on four sides

The boundary conditions for simply supported edges of plate with dimensions $a$ and $b$ are: $w = 0$, $M_{xx} = 0$ for $x = 0, a$ and $w = 0$, $M_{yy} = 0$ for $y = 0, b$. Or, $w = 0$, $\frac{\partial^2 w}{\partial x^2} = 0$ for $x=0,a$ and $w = 0$, $\frac{\partial^2 w}{\partial y^2} = 0$ for $y=0,b$. Analytical solution proposed by Levy (1899) assumes the deflection across the plate to be of form: $w(x,y) = X_n (x) \sin \frac{n\pi y}{b}$, where $n$ is an integer that satisfies simple support boundary condition @ $y=0$ and $y=b$. One advantage in this method is that subsequent series converges quite rapidly compared to a double-series representation for $w$ (Navier method). More explicitly, rectangular plate bending acted upon by pressure loading problem can be solved by taking $w(x,y) = w_o \sin \frac{\pi x}{a} \sin \frac{\pi y}{b}$ where $w_o$ is a constant that is chosen to satisfy equation (5). On solving we get:

$$w_o = \frac{pa^4b^4}{\pi^4D(a^4+b^4+a^2b^2)}$$  \hspace{1cm} (7)

Moreover, Annexure B of Bureau of Indian Standards (BIS, Feb 2013) gives a set of empirical relationships as a function of Young’s Modulus $E$, thickness $t$, aspect ratio of the plate and pressure loading acting transversely to calculate maximum deflection of glass plate. Maximum allowable deflection is taken to be as (minimum span)/125.

### 3.2 Rectangular glass panels clamped (fixed) on four sides
By applying suitable boundary conditions for clamped edges, i.e. \( w=0 \) and \( w'=0 \) across the whole boundary, we can formulate the generalized equation for this boundary condition. However, in this research paper, a method of breaking down the fourth-order partial differential equation (PDE) into two solvable PDE, is worked upon. This procedure is used by Partial Differential Toolbox of the mathematical computing language MATLAB. Toolbox PDE in MATLAB supports Dirichlet’s and Neumann’s boundary conditions and careful analysis of system of coefficients of the resultant PDE lead to generation of a graphically interactive color map-contour of the deflection profile of plate under pressure loading acting transversely on the center. The Partial Differential Equation toolbox used by MATLAB cannot directly solve the fourth-order plate equation, but it can be disintegrated into two-second-order PDE, as follows:

\[
\begin{align*}
-\nabla^2 (u_1) + u_2 &= 0 \\
-D\nabla^2 (u_2) &= p
\end{align*}
\]

Since we cannot directly prescribe boundary conditions for \( w \) as well as for \( w' \), in order to solve this, it is assumed that stiff springs that apply transverse shear force to the plate edge are distributed along the boundary. The shear force can then be written directly as:

\[
n \cdot D\nabla (u_2) = -k \cdot u_1
\]

Where, \( n \) is the normal to the boundary and \( k \) is the effective stiffness of assumed springs. The value of \( k \) must be large enough that \( w \) is approximately zero at all points on the boundary but not so large that numerical errors result because the stiffness matrix is ill-conditioned. This expression is a generalized Neumann boundary condition supported by Partial Differential Equation Toolbox. Moreover, Westergaard through his hypothesis proposed and generated experimental curves relating the ratio of moment per unit width of the plate across its diagonal and maximum deflections of slabs with the aspect ratio and pressure loading on the plates. Through experiments he arrived at several results.

\[
w_{\text{max}} = c \frac{p_s (\text{shorter span})^4}{Et^3}
\]

Table 1: Westergaard experimental curve values to obtain coefficient, \( c \)

<table>
<thead>
<tr>
<th>Aspect ratio</th>
<th>1.0</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>0.0138</td>
<td>0.0188</td>
<td>0.0226</td>
<td>0.0251</td>
<td>0.0267</td>
<td>0.0277</td>
</tr>
</tbody>
</table>

4. IN-PLANE DEFORMATION ANALYSIS

In-plane deformation response is controlled by seismic design codes provided by different countries, allowing maximum storey drift ratio. Sucouglu and Vallabhan (1997) studied both the stages and concluded the in-plane deformation response to be more critical to safety of glass plates over a period of time. Bouwkamp (1960) summed up the response computation procedure through two consecutive events, consisting of translational drift of glass plates along with their window frames. The total deformation of window frame due to translation of glass along the movement of external window
frame under influence of design force $F$ is termed as Lateral drift, $\delta_r$. A stage comes when corners of glass plate and window frame coincide, then due to fixity of corners plate starts receiving diagonal compressive forces. Deformation goes out-of-plane in a diagonal buckling mode. Latera\_l deflection, $\delta_d$ occurs due to this diagonal shortening.

$$\delta_r = 2c \left(1 + \frac{h}{b}\right)$$

$$\Delta d = \frac{b}{d} \delta_d$$

Where, $b$ and $h$ are plate dimensions, $c$ is the frame clearance and $\Delta d$ is the corresponding diagonal shortening due to compressive forces along plate diagonal. Using line integral equation and basic mechanics relationships between flexural stress, bending moment and curvature, necessary basic equations relating maximum drift ratios, amplitude of the buckling shape (sinusoidal half wave), plate geometry and maximum allowable tensile stress due to diagonal compression can be formulated. As a sample case, consider: : Frame clearance, $c=0.005\text{m}$, thickness, $t=0.005\text{m}$, maximum allowable stress of $\sigma_{\text{allowable}} = 50\text{ MPa}$ and $E=70\text{ GPa}$. NEHRP, UBC(1997) and other provisional design codes recommends the maximum allowable drift ratio ranging 0.015 to 0.02.

As a sample case, consider: : Frame clearance, $c=0.005\text{m}$, thickness, $t=0.005\text{m}$, maximum allowable stress of $\sigma_{\text{allowable}} = 50\text{ MPa}$ and $E=70\text{ GPa}$. Graph between plate dimensions and corresponding total storey drift ratios are plotted as mesh elements. NEHRP, UBC(1997) and other provisional design codes recommends the maximum allowable drift ratio ranging 0.015 to 0.02. However, evidently when they do not take into account the diagonal shortening component of drift: lateral deflection which is at least not negligible as compared to horizontal lateral drift as seen from graphs. This means having a frame clearance in order of glass thickness is a more than safe design.

5. WORKFLOW AND IMPLEMENTATIONS IN THE WEB APPLICATION

The web application is based on tri-dependency workflow, i.e., input data handling management and simple computations are performed in PHP web-script. Database software like MySQL maintains the necessary database of parameters and exports them to a pure mathematical and computational programming language MATLAB for complex simulations like solving partial differential equations, preparing contours and graph-plotting etc.
MATLAB code also includes SMTP server network based algorithm through which output/analysis results/graphs in the form of a report are sent to the user’s Email id. The complete workflow is illustrated as following:

1. Web-based forms are presented before the user prompting him to fill all important parameters like his own contact information, geometry of plate, material properties of plate, site and terrain conditions, building plan and class, address of building/region etc. to name a few. Databases are maintained using MySQL platform. The application uses its own approximately accurate GPS features to predict the wind and seismic zone of the region where the building is. Latitude-Longitude pair of cities lying along the boundaries of zones are maintained and program calculated the closest distanced city from the entered address of the building to predict to which zone the building lies in. Closest distance is calculated using Haversine formula:

$$d = 2r \arcsin \left( \sqrt{\left[ \sin \left( \frac{\varphi_2 - \varphi_1}{2} \right) \right]^2 + \cos(\varphi_1) \cdot \cos(\varphi_2) \cdot \left[ \sin \left( \frac{\lambda_2 - \lambda_1}{2} \right) \right]^2} \right)$$ (14)

Where, $d$ is the distance of two points on large sphere and $r$ is radius of sphere $(\varphi_1, \lambda_1)$ and $(\varphi_2, \lambda_2)$ are latitude-longitude pairs of points 1 and 2 in radians.

2. Design Wind pressure and Equivalent seismic forces are obtained with the help of relevant design codes as discussed in initial sections. We now have a point-pressure loading on plate acting either in-plane or out-of-plane. Since now complex equations and more profound and discrete analysis is required, PHP data is exported to MATLAB. In FEM method of preparing transverse deflection profile for clamped plates, Partial Differential Toolbox is employed. I Operational steps being:

- Creating PDE model/system through breaking high order PDE into 2\textsuperscript{nd} order equations. Figuring out suitable selection of boundary conditions.
- Setting up parameters, i.e. geometry, loading, material properties.
- Constructive Solid Geometry (CSG) creation.
Definition of coefficients for boundary conditions and general elliptic PDE that toolbox is able to solve without any error and complexity.

Mesh generation: Jiggling and refining the mesh to improve quality.

For simply supported plates, Levy's formulation of general solution of deflection is used as discussed in section 3.1. MATLAB code profiles the plate based on general of solution it has assumed as mentioned in its literature review.

3. In-plane plate deformability simulations are performed. Inter storey drift ratios are computed, given available material properties, maximum allowable stress and aspect ratio of the plate. Results are compared with design codes for safe checking. This marks the end of the application, reports are outputted to users.

Glass window panels in buildings in two major cities of India, New Delhi and Bhopal are considered to illustrate the schematic workflow of the web application.

Table 2: Input Parameters

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>New Delhi</th>
<th>Bhopal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of plate(m)</td>
<td>1.8</td>
<td>2</td>
</tr>
<tr>
<td>Breadth of plate(m)</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Latitude-Longitude of region</td>
<td>28.6139° N-77.2090° E</td>
<td>13.0827° N-80.2707° E</td>
</tr>
<tr>
<td>Terrain-Class-Type-Topography of the structure (IS 875-III)</td>
<td>Terrain2-ClassA-General-Upwind slope&gt;3°</td>
<td>Terrain2-ClassB-General-Upwind slope&gt;3°</td>
</tr>
<tr>
<td>Type of glass – Boundary Conditions</td>
<td>Reflective-Clamped/fixed on four sides(CC-F)</td>
<td>Reflective- Simply Supported on four sides(SS-F)</td>
</tr>
<tr>
<td>Distance of glass plate from ground(m)</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Area of opening(m²)</td>
<td>0.432</td>
<td>0.6</td>
</tr>
<tr>
<td>Building dimensions</td>
<td>60x50x20</td>
<td>55x50x25</td>
</tr>
<tr>
<td>Thickness of glass(mm)</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

Frame clearance, c=0.005m, Allowable stress=50MPa, $E = 71.7$ MPa, Poisson’s ratio=0.3, maximum allowable drift ratio by NEHRP=0.015 and Canadian code = 0.02.
Table 3: Output values in the application sent as analysis results to user

<table>
<thead>
<tr>
<th>Output parameters</th>
<th>New Delhi</th>
<th>Bhopal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic wind speed acc. to Wind zone map of India</td>
<td>47</td>
<td>39</td>
</tr>
<tr>
<td>Net Design Wind Speed (m/s)</td>
<td>49.35</td>
<td>41.73</td>
</tr>
<tr>
<td>Net design wind pressure (N/m²)</td>
<td>2484.13</td>
<td>1776.22</td>
</tr>
<tr>
<td>Analytical maximum transverse deflection (acc. to BIS Annex B in SS-F condition) (mm)</td>
<td>___</td>
<td>8.1 (&lt;Span/125 = 16mm, so safe)</td>
</tr>
<tr>
<td>Analytical max deflection according to Westergaard approximation in clamped (C-F) condition (mm)</td>
<td>3.37</td>
<td>___</td>
</tr>
<tr>
<td>FEM MATLAB program, maximum deflection (mm)</td>
<td>3.2</td>
<td>11.3 (&lt;Span/125 = 16mm, so safe)</td>
</tr>
<tr>
<td>Maximum plate moments Mx and My in SS-F boundary condition (N-m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Shear forces, Vx and Vy in SS-F boundary condition (N)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In-plane deformation, lateral drift ratio</td>
<td>0.0167</td>
<td>0.0175</td>
</tr>
<tr>
<td>In-plane deformation, lateral deflection ratio</td>
<td>0.0094</td>
<td>0.0150</td>
</tr>
<tr>
<td>Total inter storey drift ratio</td>
<td>0.0217</td>
<td>0.0217</td>
</tr>
<tr>
<td>Maximum buckling mode amplitude (mm)</td>
<td>82.7</td>
<td>110.4</td>
</tr>
</tbody>
</table>

![Deflection profile of clamped glass plate against transverse wind loads](image)

![Deflection profile of Simply Supported plate under transverse wind loads](image)

Figure 10: Deflection profile (New Delhi)  
MATLAB FEM Toolbox plot

Figure 11: Deflection profile (Bhopal)  
MATLAB FEM Toolbox plot

Web Application to analyze and monitor glass panel subjected to Wind and Earthquake forces
6. CONCLUSIONS

- While there are numerous existing software packages and commercialized computer programs to simulate structural analysis of glass panels in tall buildings, this study presents a developed web application that integrates relevant features of Information Technology to handle, manipulate and store the necessary data. Various concepts of structural mechanics and analysis including complex fourth order PDE bending equations are implemented and coded in computational platforms like MATLAB and networking features are used to interact directly with the user through web.

- All the application-generated results were cross-checked with the existing design codes and different provisions in order to safely conclude about the performance and behavior of the glass plates subjected to different loading. For instance, empirical provisions described by BIS(2013), UBC(1997), NEHRP, works of Westergaard, Levy(1997) were helpful in analytical comparison of maximum transverse deflection, inter-storey drift ratios, maximum moments, shear forces in simply supported panels etc.

- Two major cities of India: New Delhi and Bhopal were selected for case-study. Complete workflow of the web application was demonstrated through hypothetical glass panels installed in buildings in those cities. Maximum deflection was under maximum limit of span/125. Inter-storey drift ratio were much larger than maximum allowable value provided in design code. Linear analysis though uneconomical compared to non-linear analysis, gives safe design values. The application provides a compatible and flexible platform for Indian builders and engineers to run simulation analysis on glass panels.

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