STRUCTURAL DESIGN OF TOUGHENED GLASS FACADE USINGEURO CODE

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Synopsis

Glass panel usage was evolved from non-structural usage as windows to structural applications as facades supporting on metal framing. Glass panels now designed as self-supporting system to get fully transparent structures. Glass structures are found in extensive shapes from flat panel to complex tubes, corrugated glass. Various types of glass materialsdetails are listed. Available analytical procedures to evaluate the strength of glass facades include –linear, non-linear analysis is summarized. An overview of design rules from Indian draft code and Euro Code was summarized. Comparative study of toughened glass panel strength with Indian draft codeand Euro code provisions was performed for the suitability and limitations for usage of tempered glass in different scenarios.

Keywords: *Glass structures, toughened glass, design codes, Indian draft code, Euro code*

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1. INTRODUCTION

Glass panel usage evolved fromolden days, mainly asvessels, beads, windows and in jewelry.Even though most of the glass wares/windows in historical buildings are used as non-structural component, there was an experimental science behind the large sizes of vessels/boxes/window spans used in construction of churches and large buildings[1].

In the modern era we can find glass usage of glass elements both in non-structural and structural applications. Building construction, automobile, solar - industries are more concerned with structural integrity of glass elements with other framing members. Window glasses are found as framed as well as self supported. Self supporting[2] facades provide lighter structural loads in addition to aesthetic and fully transparent view of building.

Different usage of glass panes as membrane (enclosing or barrier) and non-membrane element was explained by Christopher[3]. The non-membrane structural glass supports the dead loads of the enclosure, and transmits the live loads to the main building structure in the form of glass fins, mullions, beams, and masonry walls.Apart from flat panels other shapes including curved, doubly curved, tubular glass sections are manufactured forserving variety of applications[4].

Literature shows that glass structures are now a day's used in all places of buildings such as façade, staircase, beam, column and roof. Connections for supporting glass elements includes such as continuous support frame with setting blocks and silicone sealants, clamps and friction grip connections. Based on manufacturing process and other properties glasses are classified as normal or annealed, toughened or tempered glass, heat-strengthened glass, reflective glass, insulating glass. Common structural properties of these glasses are shown in table-1.

General methods of analysis of glass structures are linear analysis, nonlinear analysis and finite element method. Experimental strengths or their empirical relations are mandatory for accounting the probability of material strength in different manufacturing processes. Since glass is weak in tension and post-breakage strength is not utilized, linear plate theory gives conservative values, however in case of excessive deflections (w>T or T/2, w-maximum deflection, T-thickness of glass), large deflection theory was used for calculating bending stresses and deflection.

2. DESIGN OF TOUGHENED GLASS ELEMENT

2. 1toughened Glass

Toughened or tempered glass is a strong glass which is heated to a uniform temperature of approximately 650^{o} C and rapidly cooled to induce compressive force of 770 $kg/cm^2$to 1462 kg/cm^2 on the surfaces and edge compression of the order of 680 kg/cm^2. Concept of tempering (thermal treatment) is to produce residual tensile stresses in the core of the glass and compressive stresses on and near the surfaces. The mid thickness portion of glass does not contain flaws and therefore offers good resistance to tensile stress. Flaws on glass surface will grow if they are subjected to resultant tensile stress. Tensile stresses on surface due to applied loads are smaller than residual compressive stress; hence crack growth can be arrested (Fig.1).

These glasses are strong to resist impact and fire loads. Tempering imparts strength from the compressed surfaces. On impact these glasses will break into number of small particles. Main application of these glasses are where safety and strength are important as – curtain walls of high rise buildings, escalator side plates, airports and sport complexes. The main limitation of these types of glasses is any cutting or drilling process is to be performed before the heat treatment; therefore on site fabrication changes are not possible.

2.2 Design Methodology of Indian Draft Code5for Toughened Glass Element

In addition to the calculation procedures given below, following rules will apply for design

- Procedures applicable only forwind induced loads
- Procedures are applicable to rectangular shaped panel only, with aspect ratio more than 1.5.
- Maximum allowable area of glass panels is $15m^{2.}$
- Maximum span of window glass is 4 m
- Maximum allowed deflection for single glazing = Span/125 and for double glazing = Span/175

2.2.1 Thickness (T) Of Rectangular Panes Supported On All Four Edges Iscalculated Using Following Empirical Equation-1a And 1b

Check for maximum allowable span from given figure or tables

$(P_{net} / P_f) * A = 200 * T^k$ (for $T \leq 6$ mm) ..(1a)

$(P_{net} / P_f) * A = 200 * T^k + 1900$ (for $T > 6$ mm) ..(1b)

Where, P_{net} = Net design wind pressure (N/m^2) calculate using IS875-1987, Part-3[6],

P_f = strength factor = 2.5 for tempered/toughened glass type

A = Area of glass panel (m^2)

T = Standard nominalthickness of glass (mm)

k = Constant from the table 2.

2.2.2Thickness (T) Of Rectangular Panes Supported On Two Opposite Edges Is Calculated Using Empirical Equation-2a And 2b

Check for maximum allowable span (b) from given figure or tables

$b= (3.2688 \times T) / \sqrt{(P_{net} / P_f)}$ (for $T \leq 6mm$) (2a)

$b= 2.9069 \times T / \sqrt{(P_{net} / P_f)}$ (for $T \geq 6mm$) (2b)

Where,

b = span, in m

Calculate for maximum deflection at centre of glass using the procedure given in annexure B of draft Code, as shown below

Deflection (w) = $t^* e^{(r_0 + r_1 *X + r_2 *X*X)}$. .(3a)

$X = Ln (Ln(q(a*b)2/Et^4))$ . .(3b)

$r_0 = 0.553 - 3.83(a/b) +1.11(a/b)^2 - 0.0969(a/b)^3$. .(3c)

$r_1 = - 2.29 + 5.53(a/b)-2.17(a/b)2+0.2067(a/b)^3$ . .(3d)

$r_2 =1.485 – 1.908(a/b) +0.815(a/b)^2 - 0.0822(a/b)^3$ . .(3e)

Where,

E = Young's modulus of glass

q = Net pressure on the pane (N/m^2)

a = Longer dimension (mm)

b = Shorter dimension (mm)

t = Thickness of the glass pane calculated.

2.3 Design Methodology Of Euro Code6 For Toughened Glass Element

Euro code[6, 7]design method of glass facade is based on partial factor for including any material defects such as flaws, inclusions variation of strength changes in manufacturing process. Procedure also includes combination factors for different permanent loads such as dead load and live load and other climatic loads. Design procedure of glass elements to uniformly distributed load like wind forces with combination of other loads are given in detail for different shapes including rectangle, triangle and other geometries. Maximum stress(σ_{max}), effective stress (σ_{eff}),maximum deflection (w_{max}) equations are given separately for each case in prEn13474-part-2[7]. Two different set of coefficients (k_1, k_2, k_4, for linear theory and non-linear theory) using were given for determining the stresses and deflections. Euro code[7] suggests that linear theory coefficients can be used when deflections are small, i.e. less than the half of thickness of glass panel($w_{max}< t/2$).

An overview of the procedure to be followed in design of rectangular glass facade supported on all four edges is given below.

[1]. Choose type of glass as thermally toughened glass

[2]. Find partial factors for variation in strength of material, γ_m(1.8 for ultimate limit state and 1.0 for serviceability limit state) and γ_v(2.3 for ultimate limit state and 1.5 for serviceability limit state)compressive surface forces resulting from inhomogeneity of material from prEn13474-part-1[6].

[3]. Find design load for ultimate limit state and serviceability limit state using combination factors given,fromprEn13474-part-2[7]using equations 4a and 4b,

[4]. $F_d= \sum\gamma_G G + \gamma_Q Q$, for ultimate limit state (γ_Q =1.5)… (4a)

[5]. $F_d= \sum\gamma_G G + \gamma_Q Q$, forand serviceability limit state (γ_Q =1.0)… (4b)

[6]. G=0, as only wind load (Q) is consideredin present calculations

[7]. Find normalized load, $p^* = \frac{b^4}{t^4}\frac{F_d}{E}$... (5)

[8]. Find stress and deflections using equations5, 6, 7 as given for rectangular glass panes supported on four edges

Maximum tensile stress, $\sigma_{max} = k_1 \frac{b^2}{t^2} F_d$ … (6)

Effective stress, $\sigma_{max} = k_2 \frac{b^2}{t^2} F_d$ … (7)

Defection, $w_{max} = k_4 \frac{b^4}{t^3}\frac{F_d}{E}$ … (8)

Where b= Shorter dimension of panel

k_1, k_2, k_4 are Coefficients given in tables for normalized load (q*)with reference to different aspect ratios

a) Find allowable stress ($f_{g,d}$)for pre-stressed i.e toughened glass element using equation 9

b)

$$f_{g,d} = \left[\frac{f_{b,k}-f_{g,k}}{\gamma_m} - k_{mod}\,\frac{f_{g,k}}{\gamma_m k_A}\right]\gamma_n \ \ldots \qquad (9)$$

Where

γ_n = 1.0,(common to many nations) National partial factor from prEn13474-part-1[6]

$f_{b,k}$ = 120 N/mm^2,Characteristic fracture strength of borosilicate pre-stressed (toughened glass) from prEn13474-part-[6]

$f_{g,k}$ = 45 N/mm^2, General characteristic inherent strength of borosilicate (toughened glass) from prEn13474-part-1[6]

$f_{b,k}$-$f_{g,k}$ = Contribution of residual stress to failure strength

k_{mod} = 0.72, Modification factor for accounting the duration of load

k_A=$A^{0.04}$,Size factor determined from area of glass panel

c) Check whether the stresses and deflections are in allowable values, deflectioncriteria must also satisfy correspondingnational code provisions.

3 MODEL CALCULATIONS OF FAÇADE DESIGN

3.1 Model Calculation Using Indian Draft Code

As a part of this paper, model calculations were performed to find the thicknesses and deflections of glass façade of multistory commercial complex of 18 mx24 m plan dimensions and height of 60 m situated in Visakhapatnam location.Separatecalculations performed for wind speeds corresponding to normal basic wind speed (50 m/s) given in code[8] and Hud-Hud cyclone wind speed of 225 Km/hr (62.5 m/s).Average story height of 4 m and frames are spaced 6m c/c in both directions was considered.

Design

Discontinuous façade between each floor slab with single pane toughened glass of 1.5 m width x 3.6 m height was assumed for construction.

Therefore corresponding area of glass pane, A = 1.5 x 3.6 = 5.4 m^2

Wind Loading Calculations Are Performed With Procedure Given Below

The net design wind pressure (P_{net}) calculated using procedure of IS 875-1987, Part-3[8] was shown along with other parameters.

Aspect ratio of building = h/w =60/18=3.3,

Risk coefficient, k_1=1.0, for terrain category-1 for sea side facing window/façade glazing, structure of type class-A, Mean probable life of 50 years.

Terrain Factor,k_2 = 1.05, 1.09, 1.12, 1.15, 1.20 at 10, 15, 20, 30, 50 to 60 m heightsrespectively.

By interpolationk_2 at different storey height was calculated and shown in table-3,

Topography Factor, k_3 = 1.0

Force coefficient, C_p=1.7 foran assumed permeability in the range of 5%-20% openings

Basic wind pressure, p_z= 0.6 v_z^2... (10)

v_z= $v_b.k_1.k_2.k_3$ ... (11)

Where,

v_b – basic wind speed based on visakhapatnam location from- IS 875 Part-3[8]= 50 m/s

p_z – basicwind pressure N/m^2 at height H

P_{net}- design wind pressures on each facade element at corresponding height = p_z. C_p ... (12)

Calculatedthickness required and corresponding deflection are shown in table-3 and table-4

3.2 Model Calculation Using Euro Code6, 7

Using the above mentioned Euro code procedure for design of rectangular façade supported on all four edges, calculationswere made for same building example taken for Indian draft Code comparison.Same wind loads are generated using Indian standard IS 875-1987, Part-3[6]was used. Details of calculationsincluding maximum stress, effective stress, allowable stress, maximum deflections are given in table-5 and table-6

4. CONCLUSIONS

For most of the heights two design procedures Indian draft code and Euro codegivesconservative design.There was a difference in calculated deflections;this is due to considering separate partial factors for material strength, residual stresses and manufacturing process in Euro code, where as in Indian Draft code procedure a single safety factor was used. For higher design loads Euro code prediction is un-conservative comparative to Indian draft code, therefore next higher thickness of the glass panel to be selected. Deflection calculation method of Indian draft code was same as ASTM E-1300-2004[9.] The effective stresses are on conservative side for higher thickness. This shows that there was a large need to study the different code provisions for creating a commoncode for glass design.

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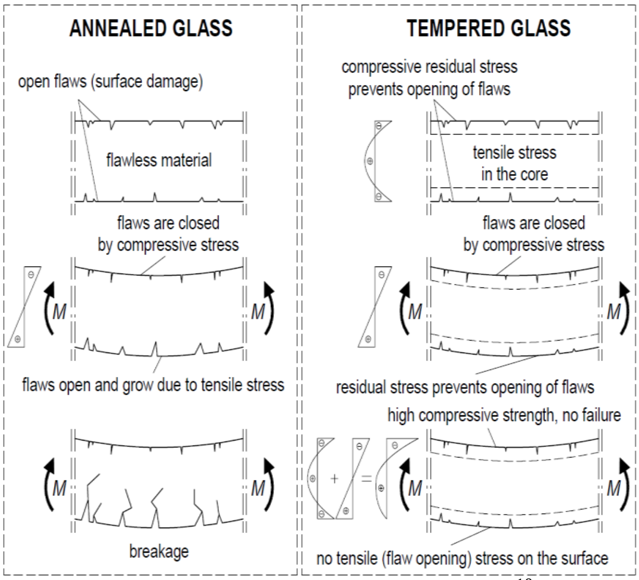

Figure-1 Principle of glass Tempering[10]

Table-1 Typical structural properties for different types of glass

Property	**Annealed Glass**	**Tempered or toughened glass**	**Laminated glass**
Tensile strength (N/mm^2)	40	120 - 200	32
Thickness (mm)	2 - 19	42082	4.38 - 20.76
Density (g/cm^3)	2.42-2.52	2.42 - 2.52	2.42 - 2.52
Modulus of elasticity (GPa)	70	70	70
Coefficient of linear expansion (m/m K)	9x10-6	9x10-6	9x10-6
Compressive strength	1000	1000	1000
Normal sizes (mm)	2440 x 3660	2440 x 3660	2000 x 3210

Table-2 k value for the corresponding Standard Normal Thickness

T	3 mm	4 mm	5 mm	6 mm	8 mm	10 mm	12 mm	15 mm	19 mm	25 mm
k	1.683	1.732	1.753	1.765	1.57	1.578	1.583	1.579	1.569	1.569

Table-3 Design thicknesses and deflections of glass façade with different floor heights of building for basic wind speed of 50 m/s using Indian Draft Code

Height	**k_2**	**P_{net} /P_f**	**Thickness**	**w- actual**	**w-allowable**
m		**N/m^2**	**mm**	**mm**	**mm (L/125)**
up to 8	1.05	1125	8	16.5	28.8
12	1.07	1168	8	17.0	28.8
16	1.10	1234	8	17.7	28.8
20	1.12	1279	10	11.3	28.8
24	1.13	1302	10	11.5	28.8
28	1.14	1326	10	11.6	28.8
32	1.17	1396	10	12.2	28.8
36	1.18	1420	10	12.3	28.8
40	1.18	1420	10	12.3	28.8
44	1.19	1444	10	12.5	28.8
48	1.20	1469	10	12.7	28.8
52	1.20	1469	10	12.7	28.8
56	1.20	1469	10	12.7	28.8
60	1.20	1469	10	12.7	28.8

Table-4 Design thicknesses and deflections of glass façade with different floor heights of building for Hud-Hud cyclone wind speed of 62.5 m/susing Indian Draft Code

Height	**P_{net} /P_f**	**Thickness**	**w- actual**	**w-allowable**
m	**N/m_2**	**mm**	**mm**	**mm (L/125)**
up to 8	1757.109	12	9.4	28.8
12	1824.684	12	9.8	28.8
16	1928.438	12	10.3	28.8
20	1999.2	12	10.6	28.8
24	2035.059	12	10.8	28.8
28	2071.238	12	10.9	28.8
32	2181.684	12	11.5	28.8
36	2219.138	15	6.2	28.8
40	2219.138	15	6.2	28.8
44	2256.909	15	6.3	28.8
48	2295	15	6.4	28.8
52	2295	15	6.4	28.8
56	2295	15	6.4	28.8
60	2295	15	6.4	28.8

Table-5 Euro code design stresses and deflections for different floor heights of building for basic wind speed of 50 m/s

Height	t	P_{design}	$f_{g,d}$	F_d	k_1	k_2	σ_{max}	σ_{eff}	k_4	F_d	w_{max}
m	mm	N/m^2	N/mm^2	N/m^2			N/mm^2	N/mm^2		N/m^2	mm
up to 8	8	2811	49.4	4217	0.372	0.322	55.2	47.7	0.085	2811	34
12	8	2919	49.4	4379	0.368	0.316	56.7	48.7	0.084	2919	35
16	8	3086	49.4	4628	0.361	0.308	58.7	50.1	0.082	3086	36
20	10	3199	49.4	4798	0.479	0.427	51.7	46.1	0.109	3199	25
24	10	3256	49.4	4884	0.477	0.425	52.4	46.7	0.108	3256	25
28	10	3314	49.4	4971	0.473	0.422	52.9	47.2	0.106	3314	25
32	10	3491	49.4	5236	0.465	0.415	54.8	48.9	0.105	3491	27
36	10	3551	49.4	5326	0.462	0.413	55.4	49.5	0.105	3551	27
40	10	3551	49.4	5326	0.462	0.413	55.4	49.5	0.105	3551	27
44	10	3611	49.4	5417	0.459	0.41	55.9	50.0	0.105	3611	27
48	10	3672	49.4	5508	0.457	0.408	56.6	50.6	0.105	3672	28
52	10	3672	49.4	5508	0.457	0.408	56.6	50.6	0.105	3672	28
56	10	3672	49.4	5508	0.457	0.408	56.6	50.6	0.105	3672	28
60	10	3672	49.4	5508	0.457	0.408	56.6	50.6	0.105	3672	28

Table-6 Euro code design stresses and deflections for different floor heights of building for Hud-Hud cyclone wind speed of 62.5 m/s

Height	t	P_{design}	$f_{g,d}$	F_d	k_1	k_2	σ max	σ eff	k_4	F_d	w_{max}
m	mm	N/m^2	N/mm^2	N/m^2			N/mm2	N/mm2		N/m2	mm
up to 8	12	4393	49.4	6589	0.543	0.481	55.9	49.5	0.117	4393	22
12	12	4562	49.4	6843	0.537	0.477	57.4	51.0	0.116	4562	22
16	12	4821	49.4	7232	0.529	0.47	59.8	53.1	0.116	4821	23
20	12	4998	49.4	7497	0.524	0.465	61.4	54.5	0.115	4998	24
24	12	5088	49.4	7631	0.521	0.463	62.1	55.2	0.115	5088	24
28	12	5178	49.4	7767	0.518	0.46	62.9	55.8	0.114	5178	25
32	12	5454	49.4	8181	0.509	0.453	65.1	57.9	0.113	5454	26
36	15	5548	49.4	8322	0.614	0.54	51.1	44.9	0.124	5548	15
40	15	5548	49.4	8322	0.614	0.54	51.1	44.9	0.124	5548	15
44	15	5642	49.4	8463	0.613	0.539	51.9	45.6	0.124	5642	15
48	15	5738	49.4	8606	0.611	0.538	52.6	46.3	0.124	5738	15
52	15	5738	49.4	8606	0.611	0.538	52.6	46.3	0.124	5738	15
56	15	5738	49.4	8606	0.611	0.538	52.6	46.3	0.124	5738	15
60	15	5738	49.4	8606	0.611	0.538	52.6	46.3	0.124	5738	15