

Analytical and Experimental Investigation of Post-tensioned Tempered Glass T-Beams

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Abstract - Construction materials used for buildings and bridges show significant changes during the course of last centuries. While stone, bricks, adobe, and timber had traditionally been the main construction material, the 20th century has been dominated by reinforced concrete and steel especially for tall structures. Strength, ductility, and unit weight are the major concerns in structural design, while appearance is more important from architectural point of view. Recycling is becoming more important from sustainability and environmental aspects. Glass being brittle in nature has always raised concerns to be used as a structural material. However, recent studies show that glass may become a structural material with its high compressive strength in the order of 400 MPa to 800 MPa accompanied by large bending induced tensile strength in the order of 120 MPa when tempering is used. This opens new possibilities for architectures and civil engineers: recently staircases, pedestrian bridges, and larger window glasses are being used. This study focuses on using tempered glass with post-tensioning, which is a carefully engineered technique to use an exquisite material glass in structural engineering for beams and columns. Tempering causes outer layers of glass to be evenly compressed while being in equilibrium with internal forces at the core as tension. Especially bending stresses are well tolerated in tempered glass panels. This study focuses on post-tensioned glass for theoretical design and laboratory loading experiments on T-beams. Hand calculations for post-tensioned tempered glass beams (PTTGB) had good correlation with FEM and test results. The ultimate capacity of tempered glass beams is much larger than regular glass beams but brittle behaviour at failure requires larger safety margins; furthermore, plastic coating or lamination is needed to prevent small glass pieces to shatter around.

Keywords: tempered, glass, beam, test

1. Introduction

Glass is composed of silica-SiO₂ (70-74%), soda-Na₂O (12-16%), lime-CaO (5-12%), and other chemical elements, which influence transmittance, thermal properties, tensile strength, fracture toughness, and colour. The flat surface of glass is first obtained by Pilkington and Bickerstaff in 1958 by floating glass on another molten thin to achieve constant thickness and perfect flatness. Glass panels are “tempered” by first heating to a level of melting and then quickly cooling the surface to get a stiff outer shell. In the meantime, the interior remains soft, cools off later, shrinks, and goes into tension while generating compressive stresses on the outer shell (Figure 1). The compressive stresses on the outer shell improves the bending strength of glass. Types of glass panels are generally categorized as fully float, tempered, heat strengthened, laminated, reinforced, and insulated etc. Certain laminates and admixtures might improve brittle nature of glass. Commonly glass has a density of (ρ)=2500 kg/m³, elastic modulus (E)=70 GPa, shear modulus (G)=30 GPa, and Poisson's ratio (ν)=0.23. Both tempered and toughened glass are produced by cooling heated float glass rapidly by cold air jets. The net force integrated over the cross section of glass remains zero; however, outer surfaces are under compression in two horizontal directions while inner core is under tension. Net stresses in the orthogonal direction to the glass surface remains zero except for the edges. Especially when glass is loaded under bending, surface cracks will not initiate unless the outermost layers go into net tensile stress. Fully tempered glass usually breaks into small pieces (Figure 2). Shattering of tempered glass may be improved by using a transparent PVB layer, which is often times placed between two layers of tempered glass (or more) generating laminated glass.

The objective of this study is to obtain response of post-tensioned tempered glass T beams under bending. Literature review indicates there are almost no studies on post tensioned bending tests on tempered beams. Material tests were

conducted to obtain strength and elasticity of tempered glass samples used in the laboratory tests. Hand calculations and Finite Element Model analyses were conducted and compared against the laboratory tests.

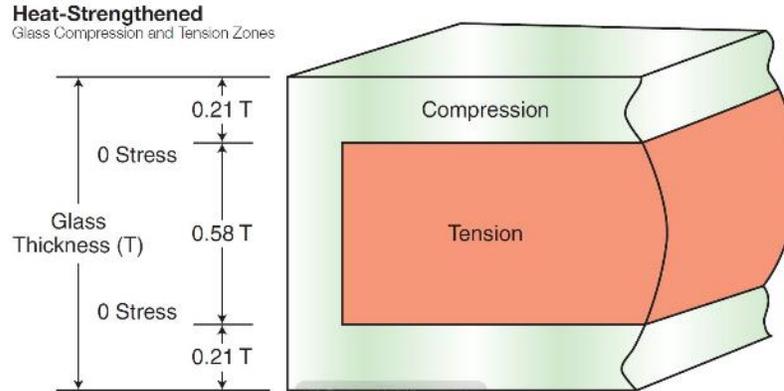


Fig. 1: Stress distribution in a tempered glass section [1].



Fig. 2: Breaking patterns of tempered and flat glass [2].

2. Material Tests

Six samples of 1000x200x60 mm dimensions tempered glass samples were tested in bending to obtain bending strength. Three of the samples were tested in their weak axis while the other were testing in their strong axis directions. The test setup and load deflection graphs are shown in Figure 3. The 4 point loading test results were post processed to obtain the stiffness, which is then used to obtain bending stress capacity. Elastic modulus was also obtained from the deflections. The characteristic strength for 5% is obtained by subtracting 1.65 times the standard deviation from mean to obtain the strength that will represent 95% of the tempered glass population from the lower side. In other words, 95% of all samples will have bending strength and elastic modulus larger than the presented values. The mean bending test based tensile strength is obtained as 174.80 MPa with 3.35 MPa standard deviation, and 169.28 MPa 5% characteristic strength in the strong axis and 121.70 MPa in weak bending axis. The 5% elastic modulus was obtained as 62.58 GPa in strong axis while theoretical value is 70 GPa. The tempered glass bending based tension strength is also found as 120 MPa in the literature, most probably referring to the bending strength in the weak axis. Since T-beam will have the web section in strong axis, the tensile strength should be considered as 174.80 MPa, which is an interesting finding of this study. When the beams are placed on their strong axis, the edge of the glass has a higher tensile strength, about 44% larger than the weak axis. Tempered glasses are often used as windows and their governing tensile strength is in the weak direction bending.

The test setup was composed of a top beam to apply load at L/3 and 2L/3 points and an LVDT with 100mm stroke with 0.006mm resolution was used at the center of the beam. Load cell had 3mV/V output and had resolution of 5N for its full range of 50 kN. Campbell Scientific CR1000 model data logger was used to digitize and record test date.

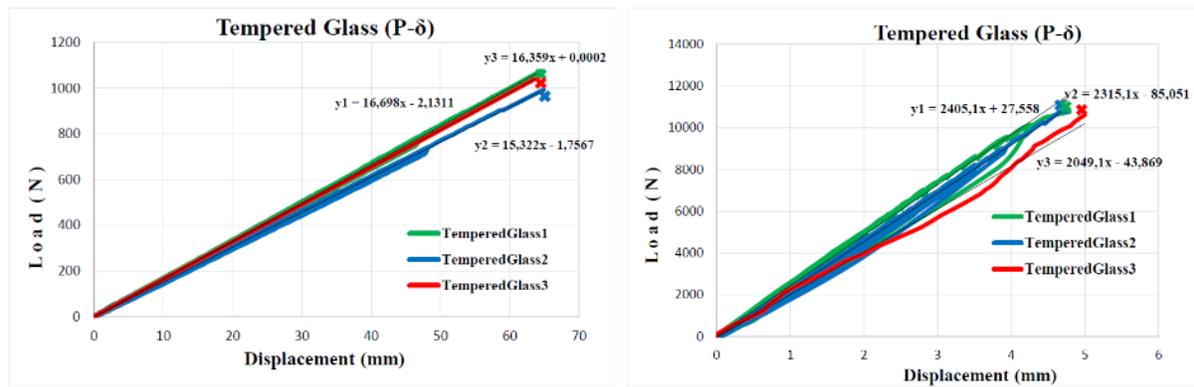
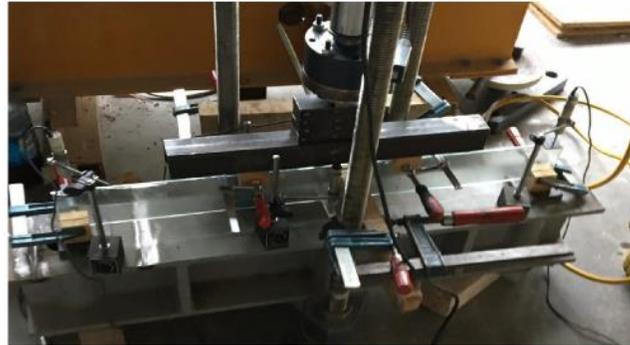


Fig. 3: Load-displacement graph of tempered glass samples placed in their weak and strong axes.

3. Post-tensioned Glass T-Beam Calculations

The calculation of capacities of test beams were conducted by simple hand calculations and shell based finite element modelling. Due to statically determinate nature of the simply supported test beams, the capacity calculations using common strength of materials approach was quite satisfactory. Other relatively complicated stress distribution towards the supports were obtained by FEM results; however, maximum bending region was the governing condition to determine ultimate load capacity of the beams.

The calculation were conducted for T-shaped beams that were composed of two tempered glass members of 1m long, 100mm wide, and 6mm thick. The two members are glued together in orthogonal direction using two L shaped aluminium angles with 15x15x1.2 mm dimensions by the help of polyurethane based adhesive (Akfix 610) as bonding material to form a T-shaped glass beam (Figure 4).

3.1. Hand Calculations of T-Beams Capacity

Simply supported T-Beam specimens with dimensions of 1000x106x6 mm were tested under 8-point loading. The main reason of using a distributed load tests was it was not found in the literature although distributed loads are quite common for post-tensioned beams. An 8-point loading distribution is assumed to closely resemble the distributed loading on a beam and a 2nd order polynomial post-tensioning cable orientation was selected to best carry the distributed load (Figure 5).

Preliminary hand calculations were done for tempered glass T-beams with post-tensioning according to the characteristic strength (169.28 MPa) and modulus of elasticity (62.58 GPa) of tempered glass obtained from the material tests. Simple deflection, maximum shear force, moment calculations, post-tensioning effects are considered and iteratively determined to

satisfy transfer case, bending (tension-compression), bearing failure, shear strength using an Excel sheet and equations provided in Figure 5. Stress check calculation results for glass beam with and without post-tensioning are done using sheet after optimization for both in transfer (short term) and final (long term) cases and tabulated below (Table 1).

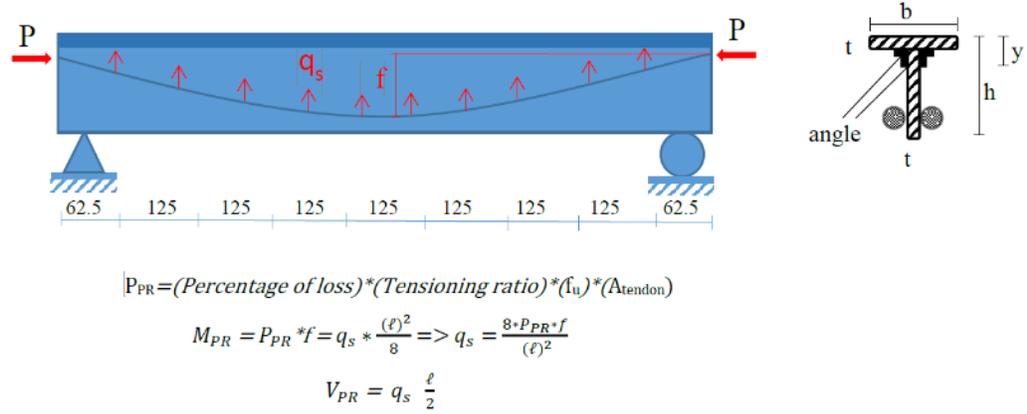


Fig. 4: Demonstration of loads on T-beam and relevant equations.

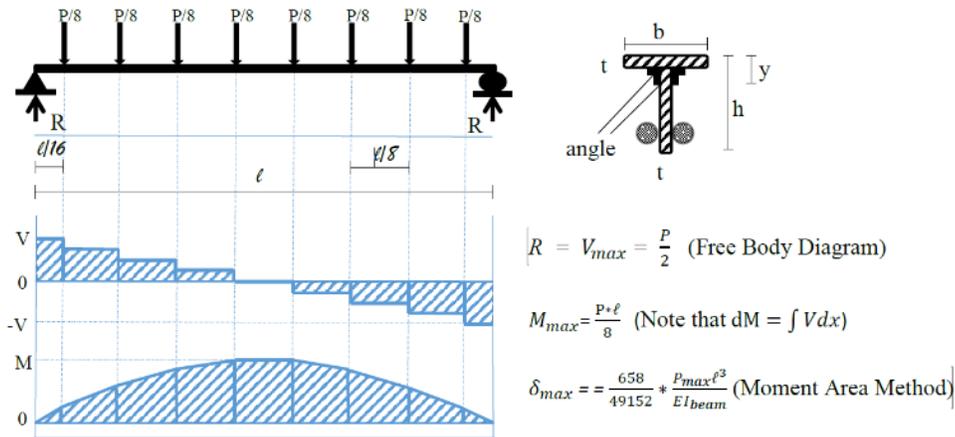


Fig. 5: Shear and Moment Diagrams of the Test Beam.

Table 1: Calculated results of T-beam with and without post tensioning (tempered).

	Post-tensioned T-beam		T-beam without Post-tensioning		
	Design Results	Ultimate Results	Ultimate Results		
Transfer Case	P_{PR} (kN)	21.54	21.54	P_{max} (kN)	25.19
	$\delta_{transfer}$ (mm)	1.60	1.60	δ_{max} (mm)	3.37
	σ_{top} (MPa)	13.20	13.20	σ_{top} (MPa)	-61.94
	σ_{bottom} (MPa)	-99.38	-99.38	σ_{bottom} (MPa)	169.27
	$P_{des./crack/ult.}$ (kN)	19.28	39.97	$\tau_{neutral axis}$ (MPa)	25.83
	δ_{final} (mm)	0.98	3.754	$\tau_{glue point}$ (MPa)	21.79
	σ_{top} (MPa)	-34.22	-85.12	-	-
	σ_{bottom} (MPa)	30.20	169.47	-	-
	$\tau_{neutral axis}$ (MPa)	9.04	21.54	-	-
	$\tau_{glue point}$ (MPa)	7.63	1.60	-	-

As seen in the table, the load carrying capacity of the beam is increased by about 1.6 times (increased from 25.19 kN to 39.97 kN) the original case without post-tensioning.

3.2. Analytical Modelling of the T-Beams

SAP2000 (v.20) analysis software was used for the generation and simulation of loading conditions on Finite Element Models (FEMs) of the post-tensioned tempered glass T-beams. Glass was modelled as thin shells with 12.5x12.5 mm mesh size, aluminium L shaped angles as frame sections, and post-tensioned wire rope as tendon. Post-tensioning load after losses was calculated as 21.54 kN for tempered glass and applied on double tendon members on both sides of the web glass. After tendon preloading, the beam was also loaded to the ultimate stage to obtain the stresses at top and bottom of the mid-span (Table 2). The model results were obtained for transfer (Figure 6) and final loading cases (Figure 7). FEM results of T-beams with and without post-tensioning at their mid-spans are also tabulated in Table 2. The loading condition for the final loading case in Figure 7 was obtained for the loading case of Pult being 39.97 kN and evenly distributed to 8 loading points with about 5 kN acting at each loading point.

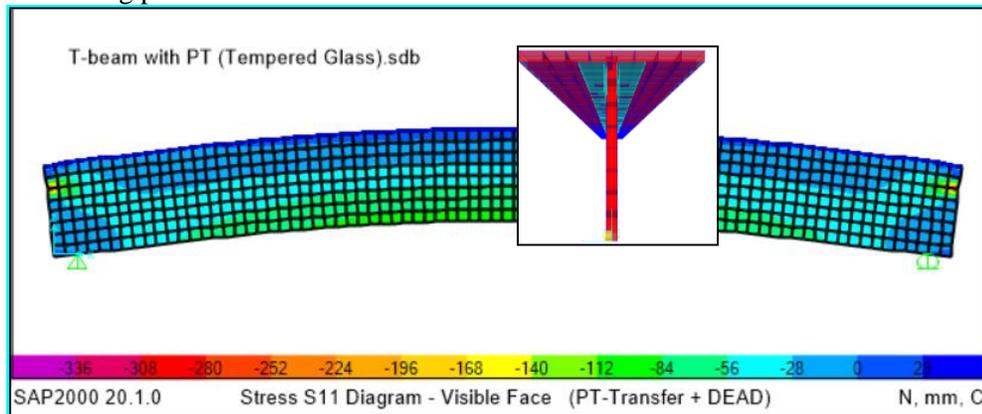


Fig. 6: Stresses at transfer case of post-tensioned float glass T-beam

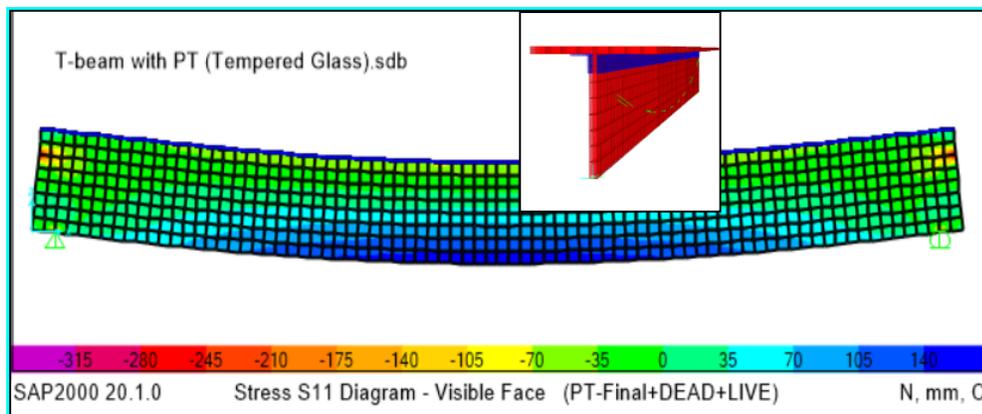


Fig. 7: Stresses at final case of post-tensioned float glass T-beam

When the finite element model results (Table 2) were compared against the hand calculations (Table 1), they both have very close results for tempered glass, with and without post-tensioning. Although not evaluated in the hand calculations, the FEM results show that there are stress concentrations at the point of post-tensioning application. The compressive stresses reaching at 300 MPa range may still be tolerated in the experiment, but it is a good practice to distribute glass end force to a larger area. Therefore, proper precautions are taken in the laboratory to reduce stress concentrations at the beam ends.

Table 2: FEM results of T-beam with and without post tensioning

	T-beams without PT	T-beams with PT	
		Transfer Case	Final Case
δ_{\max} (mm)	3.64	1.84	3.92
$\sigma_{\max, \text{tensile}}$ (MPa)	171.3	12.86	169.3
$\sigma_{\max, \text{compressive}}$ (MPa)	-68.25	-103.3	-95.9

4. Post-tensioned Glass T-Beam Calculations

T-Beam specimens were prepared for the tests with and without post-tensioning. The web and flange of the T-Beam were 1000 mm in length, 100 mm in height, and 6 mm in thickness. The composite action between the flange and web parts of the glass T-beam was utilized using two aluminium L15x15x1.2mm profiles by the help of polyurethane based adhesive (Akfix 610-conforms to D4 according to DIN EN 204). The aluminium type is AA6063-T6 which has about 152 MPa shear strength and its modulus of elasticity is the same as the glass (70 GPa). The test beams were restrained from either side for additional stability which will not be necessary in real case applications because of the flange and deck will have lateral stability since the deck will be continuous between girders. Effective width of the deck is considered to be 100m in this experiment. Post-tensioning tendon was selected as 8 mm diameter galvanized steel wire rope. The post tensioning was performed using a hollow hydraulic jack, where a load cell is attached at the back of it. The cable passed behind a bolt on the far end, through holes of a metal plate on either side of the web, under 8 pieces of glass surface mount circular members, through the hydraulic jack, through the load cell, and finally an anchoring mechanism at the other end of the load cell. The set-up of T-beam tests with and without post-tensioning are displayed in Figure 8.



Fig. 8: Test set-up of T-beam with and without post tensioning

The load-displacement graphs of tempered glass T-beam specimens are given in Figure 9. The results for averages of maximum load (P_{\max}), maximum deflection (δ_{\max}), graph secant slope values obtained from the tempered test beams without post-tensioning are obtained as 25.19 kN, 3.28 mm, and 7.8 kN/mm, and for post-tensioned tempered glass beams as 39.97 kN, 4.05 mm, 9.8 kN/mm, respectively. The glue material satisfied full composite action and T-beam post-tensioning was found to improve structural performance by about 1.6 times based on the results. The optimum wire post-tensioning force of 21.54 kN might be different for different beam sizes and aspect ratios. The transverse condition should satisfy tensile capacity of the top flange but more importantly, compressive capacity of the bottom edge of the web. This section is susceptible to buckling since the lower tip of the web is not laterally restrained and goes under large compression during post-tensioning effect. Both of the axial force and negative bending moment generates compressive stresses and might cause the member to buckle sideways.

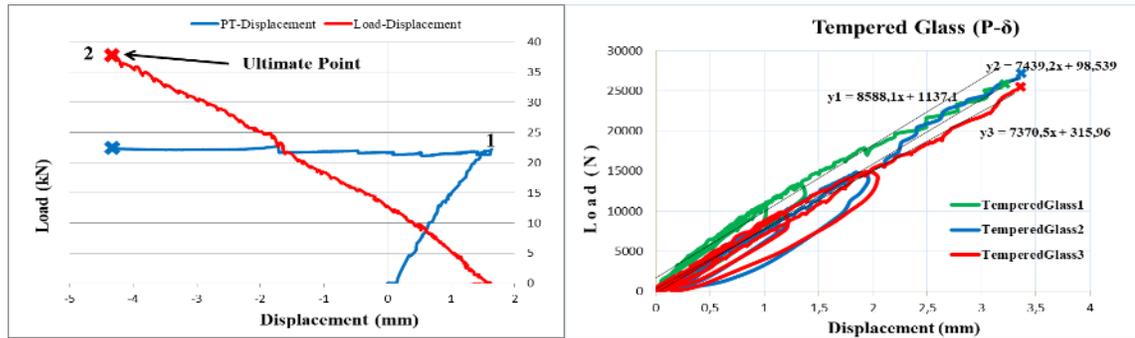


Fig. 9: Test results of T-beam with post-tensioning

5. Conclusions

This study showed that tempered glass beam is brittle in regardless of the post-tensioning (i.e., with or without post-tensioning). The strength improvement achieved by post-tensioning of tempered glass T beams was about 1.6 times as compared to the plain glass tests of the same size; however, the system did not achieve a post-cracking ductility response as it was expected. Another result of this study was that the test results showed good correlation in the range of about $\pm 3\%$ with both hand calculations and FEMs as an indication of linear elastic behaviour. Brittle nature requires higher factor of safety, but better accuracy in predicting the response may be an advantage reducing the standard deviation of bending capacities. In order to prevent shattering glass pieces, lamination films might be used to keep pieces together although brittle collapse is inevitable. UV and/or IR filters with might be used to prevent greenhouse effect.

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