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Trabes Vitreae Tensegrity: an Example of Segmental Prestressed Glass Beams

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High transparency and modularity, retarded first cracking, non brittle collapse and fail-safe design were the basic requirements that inspired and guided the development of a new kind of glass beams. The two basic conceptual design goals were to avoid any cracking at service and to get a ductile behavior at failure. These objectives were reached by anticipating and directing cracks with the subdivision of the beam into many small triangular laminated panes and by assembling them together by means of prestressed steel cables. Two prototypes have been constructed at the University of Pisa, tested in the elastic domain under dynamics loads and successively brought to collapse under quasi static, increasing load cycles. In order to investigate the decay process of residual mechanical resources, the second prototype has been repaired two times by substituting just the damaged triangular panes and then tested again each time up to failure. Non linear numerical simulations, performed by appropriate FEM modeling, resulted satisfactory able to predict and reproduce experimental results.

Keywords: Structural Glass; Prestressed Glass Structures; Post Breakage Behaviour; Structural Ductility; Fail Safe Design; Chemical Tempering; Fracture Mechanics.

1. Introduction

Ductility is usually associated to metallic materials which are capable to develop large plastic deformations. On the contrary fragility is traditionally associated to glass materials or ceramics.

Nevertheless, some famous and pioneer glass structures, like the Haus Pavillon in Rheinbach (Ludwig & Weiler), the Yurakucho canopy in Tokio (MacFarlane), the glass stairs of the Apple Stores in San Francisco (Eckersley O'Callaghan), have been built even in seismic areas where global fragile failures must absolutely be avoided.

Indeed, although glass is fragile and weakly tension resistant, it has a very high compressive strength and, if conveniently connected with other ductile materials, for example by means of gluing or prestress, it is able to form composite structures of high mechanical performances, even including global structural ductility.

It is well known that stress concentrations that occur at the apex of microscopic surface cracks, always present also in virgin specimens, are responsible of the intrinsic fragility of glass 'Menčik [1]' and of its relative low tensile strength. A apparent higher tensile strength is obtained by thermal or chemical tempering treatments which induce surface compression stresses that inhibit crack initiation and propagation but do not exert any influence on fragility 'Sedlacek [2]'.

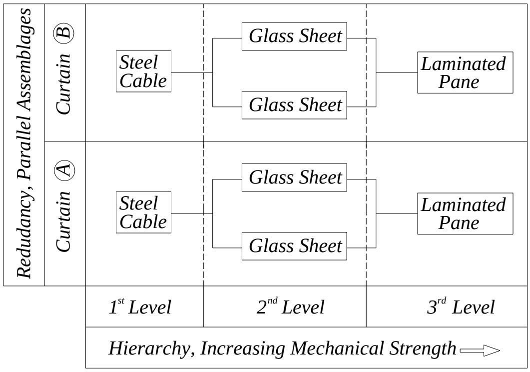


Figure 1: Hierarchy and redundancy organization.

2. Prestressed Composed Glass Beams

2.1. Basic concepts

Glass intrinsic fragility may be overcome by organizing the whole structure in two or more hierarchic levels, each of them composed by a parallel, redundant assemblage of at least two structural components.

The hierarchic organization of the components assures that the sequence of progressive damages follows a pre-established order starting from the level where the weakest components are. Therefore, if we put ductile materials at the lowest level, we are sure that the failure process starts here accompanied by large plastic deformations, i.e. with a global ductile behavior.

On the other hand, redundancy assures at each level that, when a single component fails, the other partner components are still able to bear the load although with a reduced safety degree ‘Rice&Dutton [3]’. In laminated glass panes the application of this principle assures also a pseudo-ductile behavior: it is known indeed that if a glass sheet breaks, the other sheets are still able to bear the load, and even if all the sheets break into large fragments, (only fully thermally tempered glass breaks into many small fragments), the redundant sandwich structure assures a post-breakage stiffness and bearing capacity of the component that is similar, to some extent, to material ductility ‘Kott&Vogel [4]’.

A suited application of both basic principles of hierarchy and redundancy can give a structure decisive properties of global ductility and fail-safe design even if mostly composed by glass components. Figure 1 schematizes the structural organization of the present type of glass beams.

Additionally, if the integrity of the structure is assured by prestress, compression stresses superimpose in glass elements to those produced by tempering, thus increasing the apparent tensile strength of the material.

2.2. Structural Conceptual Design of TVT Beams

Experiments reveal that when a traditional glass beam is submitted to increasing flexural loads, it cracks at a certain load stage developing characteristic crack patterns. To avoid a uncontrolled process of crack initiation and propagation, the idea was to

anticipate and to govern it by regularly pre-cutting the glass surface in many equilateral triangle panes and to connect them together by a system of prestressed steel cables.
The principle of Tensegrity permeates this conception, therefore it was decided to call these beams *Trabes Vitreae Tensegrity* or TVT, mixing Latin and English words.
Each triangular pane is composed by two 5mm thick chemically tempered glass sheets ' Macrelli [5]' laminated by means of a 1.52 mm thick PVB interlayer.
The beam is composed by two parallel twin curtains put each other at a distance of 174 mm, braced in the upper side by a horizontal truss and connected together in the lower edge knots by means of hollow stainless steel profiles (Figs. 2, 3). Each curtain is made of a Warren-like serial disposal of glass panes (Figure 2), jointed together at their apexes by means of stainless steel knots (Figure 3). Mechanical bolting between glass panes and steel knots has been avoided since dangerous local tensile peaks always occur in glass holes.
Instead of that, the knots are mutually connected by means of inox steel cables tensioned by screw tightners. Consequently, just contact pressures can be exchanged between glass and steel knots due to the prestress action. In order to attenuate local contact peaks, the vertexes of the glass panels are round and aluminium alloy sheets have been interposed between steel and glass.
The redundancy principle is applied at two different levels: the first one is that of the doubly laminated panes, the second level is that of the parallel arrangement of the two twin curtains of glass panes and steel cables as sketched in the scheme of Figure 1. The relatively large spacing of the two curtains gives the beam a appreciable torsional stiffness and good lateral torsional buckling stability.

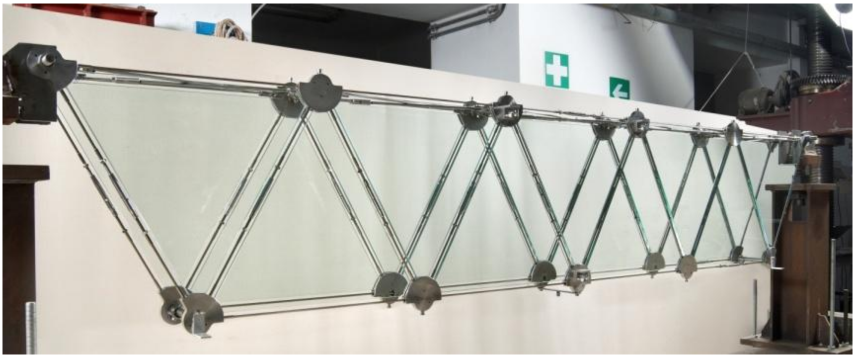


Figure 2: The prototipe TVTβ beam.

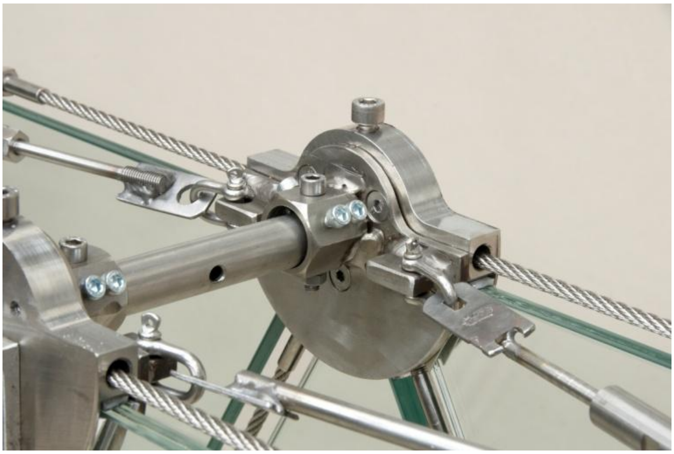


Figure 3: Steel knot.

3. Qualitative Structural Behaviour

3.1. Phase "0": pure prestress

The structural behaviour of TVT beams is analogous to that of segmental prestressed concrete beams. During the shop assemblage of a beam the two twin curtains are disposed on a horizontal plane and prestressed. Gravitational forces are entirely sustained by the surface, thus only prestress forces act inducing a quasi isotropic distribution of compression stresses in the glass panes (Figure 4).

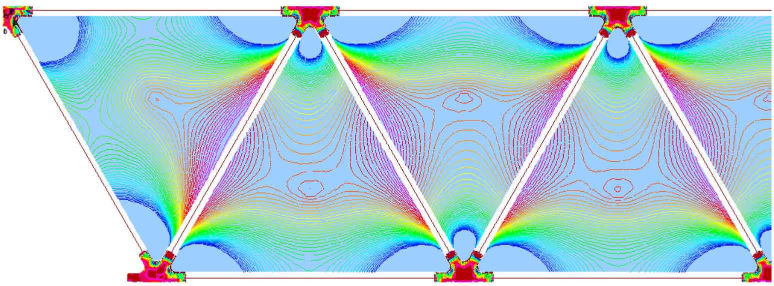


Figure 4: Phase "0"Compression isolines.

3.2. Phase "1":Glass Decompression

At service, under the flexural action of dead loads and increasing external loads, tension stresses in the lower parts of the glass panels gradually diminish prestress compressions until a limit state of decompression is reached in the central part of the beam. By further increasing the external loads the decompression propagates from middle span towards the supports. This stage has been denoted as Phase "1" – Glass decompression.

Since the steel knots exert just a contact, unilateral restraint, the decompressed vertexes of the glass panels detach and simply move a little quantity from their supports without developing tension stresses. The static scheme of the beam changes thus into that sketched in Figure 5 where flexural and shear tension forces are sustained respectively by the lower steel bars and one order of the diagonal steel bars. Compression stresses flux within the glass panels following typical “boomerang shaped” patterns visible in the same graph. Only secondary tension stresses of lower intensity afflicts glass.

3.3. Phase “2”: Buckling of upper cables

Compressed steel cables are gradually de-tensioned: when the prestress load is fully compensated they buckle away. This limit state has been denoted as “Phase 2” – Buckling phase.

3.4. Phase “3”: Collapse

After Phase “2” has been reached, a further load increasing traduces into a augmentation of stress compressions in the glass parts and tension stresses in the steel rods. The dimensioning of the different component parts of the beam can be performed so that the final Phase”3” – Collapse takes place just due to the yielding of the steel cables and not because of glass rupture in compression, thus attaining a ductile collapse accompanied by large displacements.
Depending on the slenderness of the steel cables and on the prestress intensity, Phase 2 may even follow Phase 3, as indeed happened in the prototype beam, and illustrated in the following.

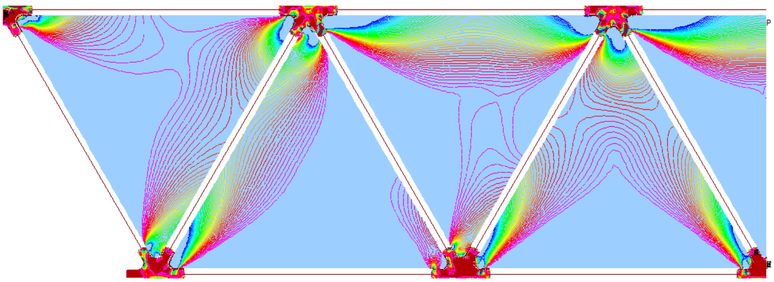


Figure 5: Phase “2”Compression isolines.

4. Numerical Modeling

Four different kinds of FEM analyses have been performed to predict the various aspects of the structural behaviour of the beam and to better calibrate the design of the prototypes:

- 2D non linear geometrical analysis to evaluate the effect of prestress on the flexural stiffness of the beam;
- 2D local buckling analysis to evaluate instability effects of prestress for each single glass pane;
- 3D local non linear geometrical analysis to evaluate the transversal stiffness of the different joints;
- 3D non linear geometrical analysis to evaluate the torsional stiffness of the beam;

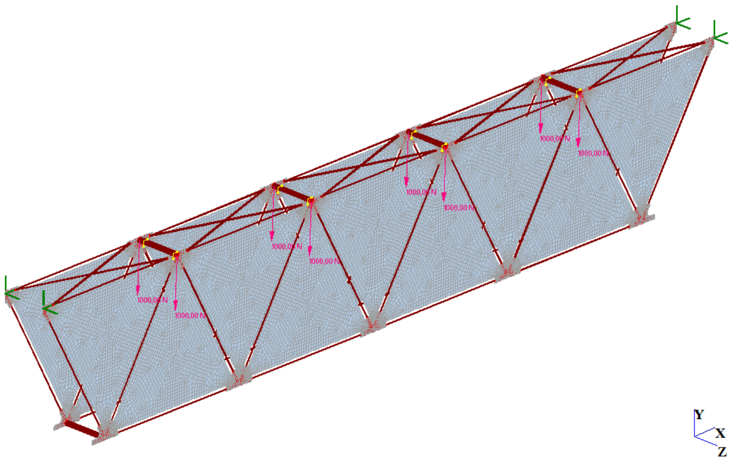
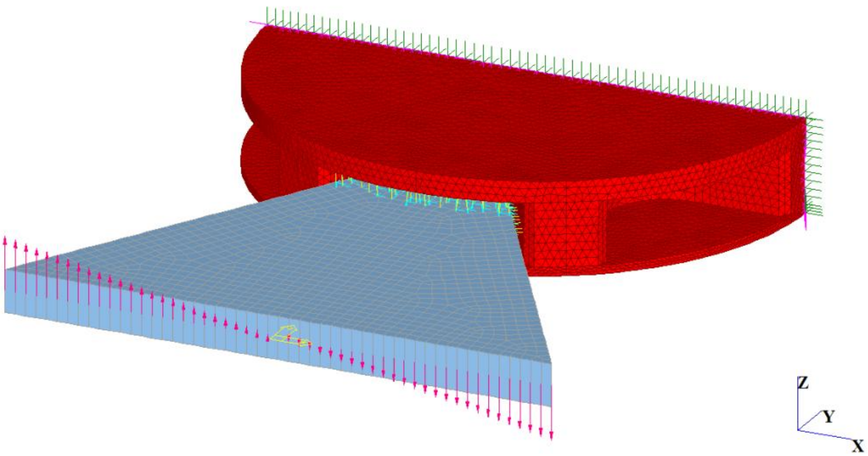


Figure 6: Global model of TVTβ.

The glass panels have been modelled by *Shell* elements while the steel cables have been reproduced by *Truss* elements able to react only to tension stresses. The implemented constitutive laws of the two materials have been deduced by available European Code [UNI EN 572] that is, glass has been schematized as a linear brittle elastic material and stainless steel as linear elastic-plastic material with a linear hardening branch.
To model contacts between glass panels and steel knots it was introduced a set of *Point Contact* elements able to react just to compression stresses. The transversal stiffness of the joint has been preliminarily investigated by a 3D local model with *Brick* elements (Figure 7).



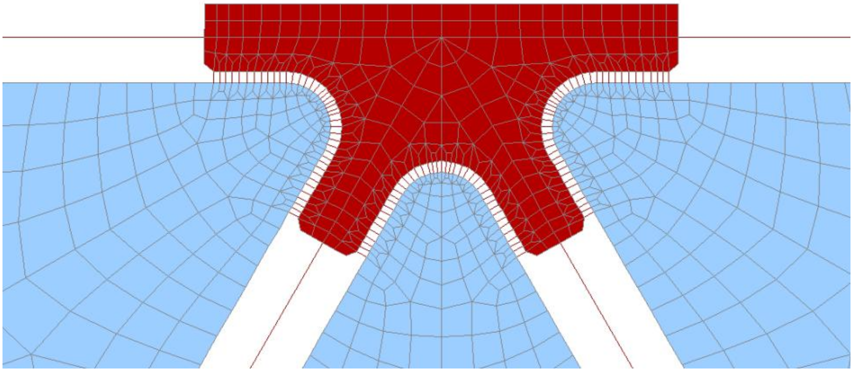


Figure 7a,b: Joint model

Calculations have substantially confirmed the intuitive predictions synthetically described at point 3 with the only exception that the buckling phase of upper steel cables (phase 2) doesn't influence significantly the flexural response of the beam. On the contrary, the decompression phase (*phase* 1) and the yielding phase (*phase* 3) of the lower steel cables can be clearly recognized.

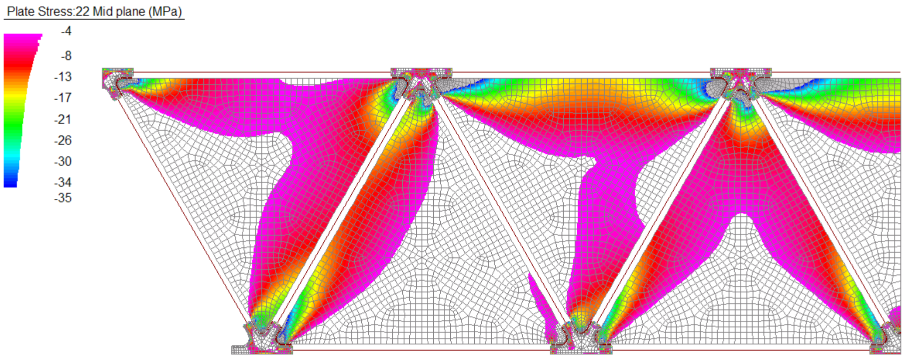


Figure 8: Principal compression stresses

Figure 9 shows the load factor versus displacement of middle span point for different prestress (from 2 kN to 12 kN) N_p load in the steel cables. The first stiffness reduction is associated to the decompression of the lower part of the beam (*Phase 1*). By increasing the prestress level the intensity of the external load that induce the decompression phase increases. The second step of stiffness decay is associated to the yielding of the lower steel cable but of course the Ultimate Limit Load results independent on N_p.
Figure 10 shows the influence of N_p on the axial force in the lower cable of the beam, and how the Ultimate Load is independent on the value of prestress.

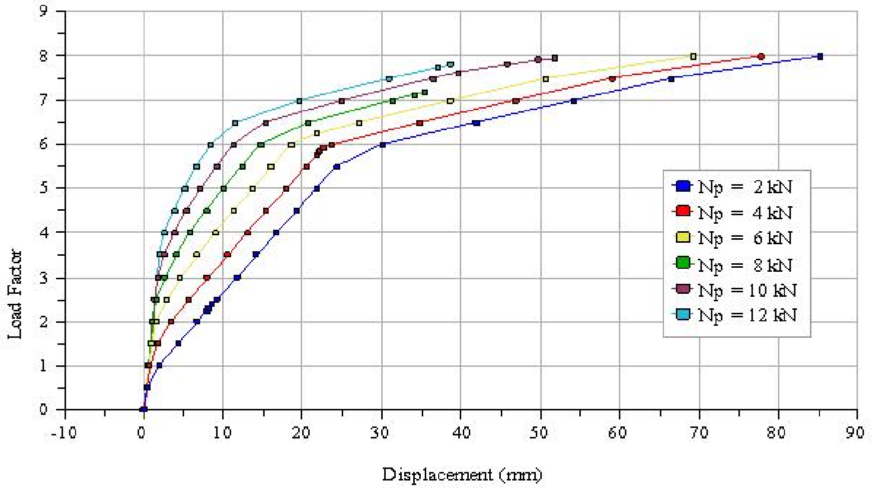


Figure 9: Load factor vs vertical displacement.

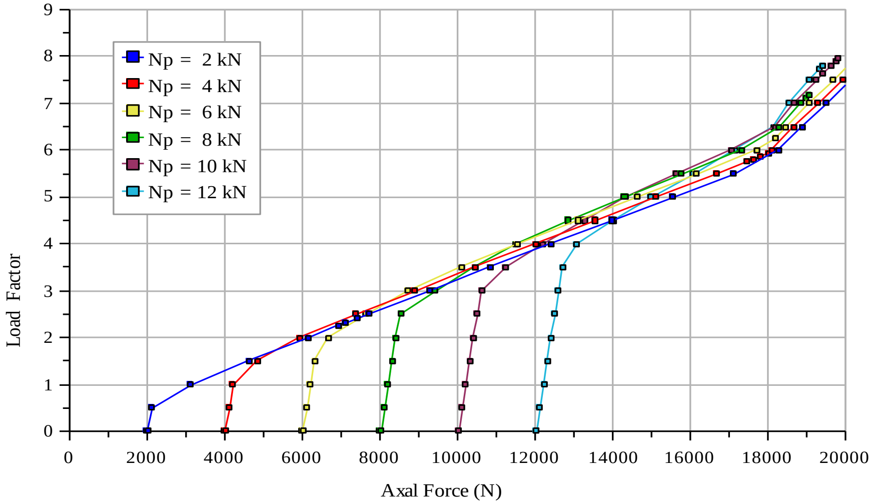


Figure 10: Load factor vs. prestress force.

The hardening properties of stainless steel allowed to prosecute the analysis beyond the yielding initiation of the lower bars till the buckling of the upper bars and of the middle span glass panels.

It can be observed that the theoretical mechanical response of the beam is substantially bi-linear until yielding of the steel bars occurs while the buckling of the upper cables seems not to have a relevant influence on the overall residual stiffness.

Furthermore, the static principle which affirms that prestress controls only Serviceability Limit States but non Ultimate Limit States is here confirmed.

5. Experimental Tests

5.1. Virgin Specimens

After the construction and testing of a first prototype (TVTα) which denounced some assemblage problems, a second prototype beam (TVTβ) was prepared having a length of 3300 mm and a height of 572 mm. This prototype has been submitted to dynamic and quasi-static cyclical laboratory tests with the purpose to completely characterize the experimental structural behavior of the specimen and to compare it with theoretical predictions.

5.2. Quasi- static cyclic Tests

The static test of TVT β prototype has been performed in two different stages : during the first one the specimen was submitted to a progressively and cyclically increasing loading condition. In the second stage the load was increased monotonically up to the collapse of the beam.

Before the application of external loads, vertical and horizontal displacements induced by self weight and prestress were measured along some days. Such investigations allowed to conclude that tension and rigidity reductions that could occur with time due to the relaxation of the cables or to other viscosity phenomena could be substantially neglected.

The program of cyclic loading has been performed to check precedent intuitions and theoretical analyses and to evaluate the different structural resources of the prototype among which: his ability to sustain repetitions of increasing loads without damage or significant performance decay, the influence of unavoidable geometrical imperfections, eventual capacity to dissipate energy without damage.

The results of the cyclic test program are represented in figure 11 in terms of applied load versus middle span vertical displacement. The experimental results are compared in the same graph with the analytical monotonic response of the 2D FEM model.

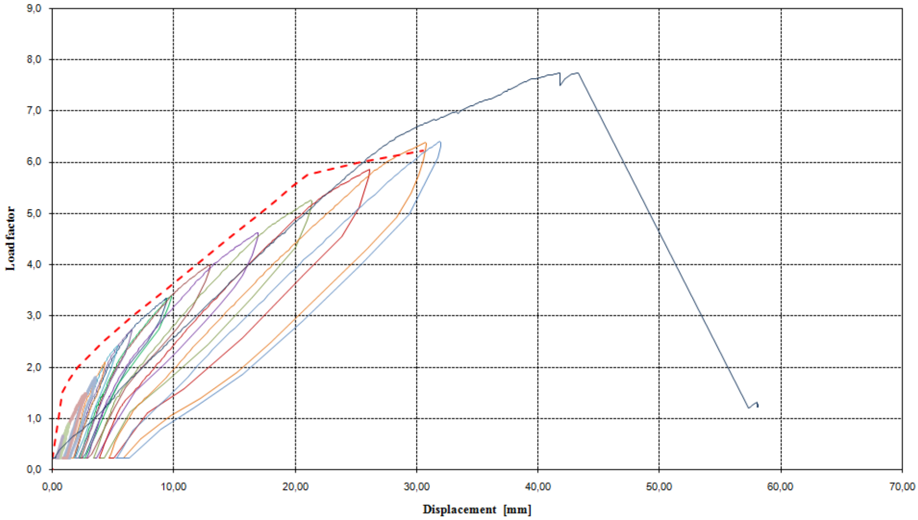


Figure 11: Load of middle point versus vertical displacement compared with F.E. model (dot line).

The comparison allows to conclude that theoretical and experimental results are rather close to each other with some limited discrepancies:

- The first knee related to *Phase "1" - Glass decompression* is recognizable although less marked as in theory;
- The actual stiffness of the beam before the first decompression knee is lower than the theoretical one;
- At each new load cycle the level of decompression load decreases in spite the residual deformation is very limited;

The graph of figure 11 shows also that the beam is surprisingly able to dissipate energy without any damage. That can be attributed to the friction that develops due to relative slip movements at the interface between glass and steel knots and perhaps also to viscoelastic slip movements in PVC interlayer.
The very small transversal displacements present at each load cycle show how good the torsion stiffness of the beam is and how it maintains constant throughout all the progression of the load cycles.
After the completion of the cyclical load program, the beam has been submitted to a monotonic increasing load up to collapse. In the graph of figure 11 the load vs. displacement curve of this stage (blue line) is compared with the theoretical one. The experimental curve has now almost any decompression knee but is now visible the second knee, corresponding to yielding of the lower steel bar, which occurred at a higher load level than predicted. First failure symptoms therefore manifested in the ductile component material of the composite structure.
Due to the hardening properties of the stainless steel, the load could be increased even beyond yielding: the final collapse of the specimen was reached when the upper parts of middle span glass panels buckled away.

Figure 12: TVTβ at failure.

5.3. Repaired Specimens

After prototype TVTβ completely collapsed as consequence of the breaking of middle span panels, it was repaired by substituting just the broken panels. Prestress was restored at the same levels of the virgin specimen TVTβ.

The first repaired prototype was labeled as TVTβbis and submitted to the same increasing load cycles of TVTβ.

Since the clam plates of the central panels in TVTβ resulted no more perfectly plane after buckling, they could not offer the same restraint degree as the virgin ones.

Therefore, the central panels of TVTβbis buckled in correspondence of a load factor of 4 instead of the precedent 7.5.

Also in prototype TVTβbis the collapsed central panels were substituted. The second repaired prototype was called TVTβtris and exhibited almost the same ultimate load factor of the precedent version.

Figure 13 collects the load factor vs. middle span vertical displacement cycles of the virgin specimen and of the two repaired versions of it. A rather good maintenance of the stiffness properties of the repaired specimens can be observed together with a progressive increase of the dissipated energy.

6. Conclusion

The numerical results and the test experiments on virgin TVTβ prototype of a prestressed composite glass-steel beam allow to conclude that the constructional principle is valid and merits further technological improvement and research work.

The experimental and theoretical results have underlined that TVT composite glass – steel beams are able to develop a ductile breakup and that the serviceability limit state is governed by the level of prestress in the steel cables. The cyclic load programme evidenced also that these glass beams are able to dissipate energy through friction and viscoelasticity without damages.

The segmental, modular features of these beams and the tensile integrity, allow to limit substitutions just to the collapsed or cracked panels thus reducing repair costs.

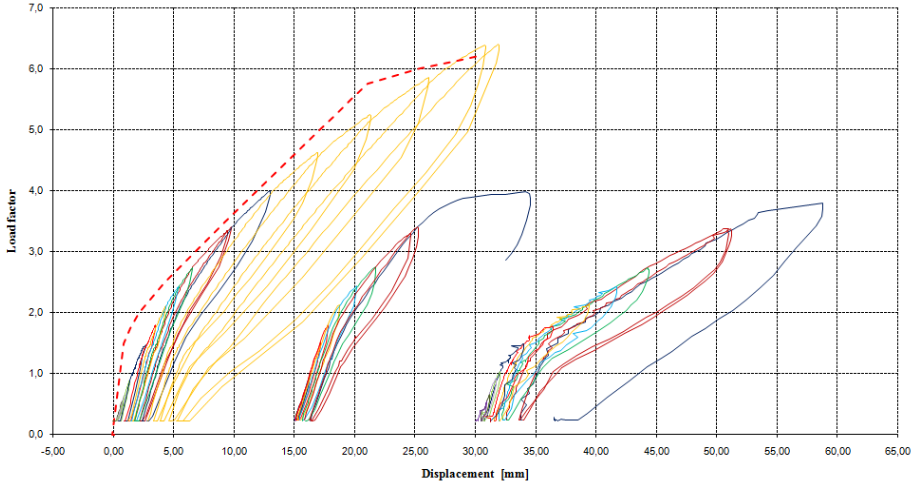


Figure 13: Displacement origins have been shifted to the right in TVTβbis / tris

7. References

[1] Menčik, Jaroslav, *Strength and Fracture of Glass and Ceramics*, Elsevier, London,1992.

[2] Sedlacek, Gerald, *Ein Bemessungskonzept zur Festigkeit thermisch vorgespannter Gläser*, Shaker Verlag, Aachen. 2000.

[3] Rice, Peter; Dutton, Hugh, *Structural Glass*, Spon Press, II° edition, London, 2004.

[4] Kott, Alexander; Vogel, Thomas, *Safety of laminated glass structures after initial failure, Structural Engineering International*, IABSE Structural Engineering International, Vol14, No2, 2004.

[5] Macrelli, Giorgio, *Process Control Methods for Chemical Strengthening of Glass on Industrial Scale*, Proc. XIX Int. Cong. Glass, Edinburgh, 2001.