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A 6 Metre Long Glass Footbridge for the Ancient Public Slaughterhouse of Pisa

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This paper illustrates the design process and the load testing of a steel-reinforced laminated glass beam built for a 6 m span glass footbridge. This specific glass footbridge has been designed and tested to join two existing floors of the main room of a refurbished masonry building of the 19th century public slaughterhouse of Pisa. To meet the needs for transparency asked by the Municipality of Pisa the beams, the running surface and the balustrades, were made of laminated glass. The project started with a design of a 5790 mm length beam which has been designed and checked using analytical and numerical modelling. Previously a series of 4-point bending experimental tests had been performed on 6 specimens of 2000 mm steel-reinforced glass beams at the University of Pisa in order to validate the accuracy of both the numerical and the analytical modelling. A final load testing has been done on the footbridge and the results have been compared with the numerical findings.

Keywords: Steel-reinforced glass beam, Structural glass design, Fail safe design, Laminated glass beam, SG, PVB, Numerical modelling, Load testing

1. Introduction

One decade ago, the Municipality of Pisa approved the refurbishment plan of a 19th century public slaughterhouse that consists of several buildings of various shapes and sizes, see figure 1a). The purpose of the project, signed by arch. Roberto Pasqualetti, was to convert some of the buildings into a scientific museum and an exhibition area, and the remaining ones into offices for high-tech start-up companies. Along with the structural work necessary to achieve the degree of safety required by the Italian construction regulations some new structural elements have been added.


a) b)

Fig. 1a) The main building of the complex of the ancient slaughterhouse, b) the indoor glass footbridge.

One of request of the Municipality of Pisa was to join the floor above the two sides of the lateral internal chambers at 2800 mm from the ground in the largest room of the main building. A small indoor glass footbridge was designed and built in order to cover the gap between the two floors, see figure 1b). The glass footbridge has a length of 6000 mm, a width of 1760 mm and it consists of a laminated glass deck, glass railings and laminated glass beams. The laminated glass deck is supported on one side by a continuous steel-reinforced laminated glass beam which has a length of 5790 mm and, on the other side, by three smaller laminated glass beams, see figures 2a) and b). The steel-reinforced laminated glass beam is simply supported at its ends and is connected to the top of the existing walls at a height of 2800 mm. The remaining laminated glass beams have a length of about 2000 mm and are supported at their ends by the existing old cast iron columns.

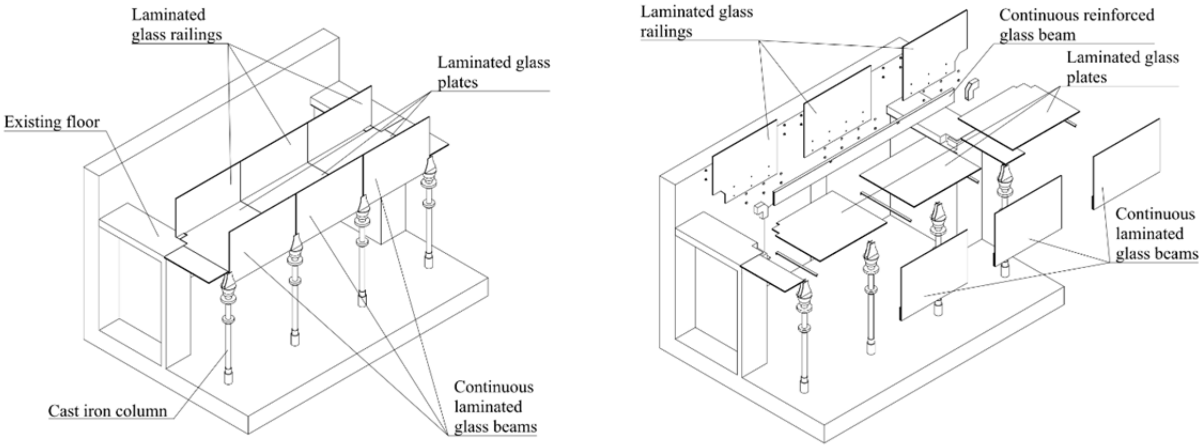
This paper reports the design of the steel-reinforced laminated glass beam, the design loads, the load combinations, the verifications, the numerical and the analytical modellings. Furthermore, the load testing of the footbridge is described. Finally a comparison of the numerical, analytical and load testing results is reported.

a) b)

Fig. 2a) and b) The steel-reinforced laminated glass beam viewed from different positions.

2. Description

Figure 3 shows the two floors that had to be connected and the existing old cast iron columns. The load bearing structure is made by a single continuous steel-reinforced laminated glass beam alongside with three other shorter continuous laminated glass beams.

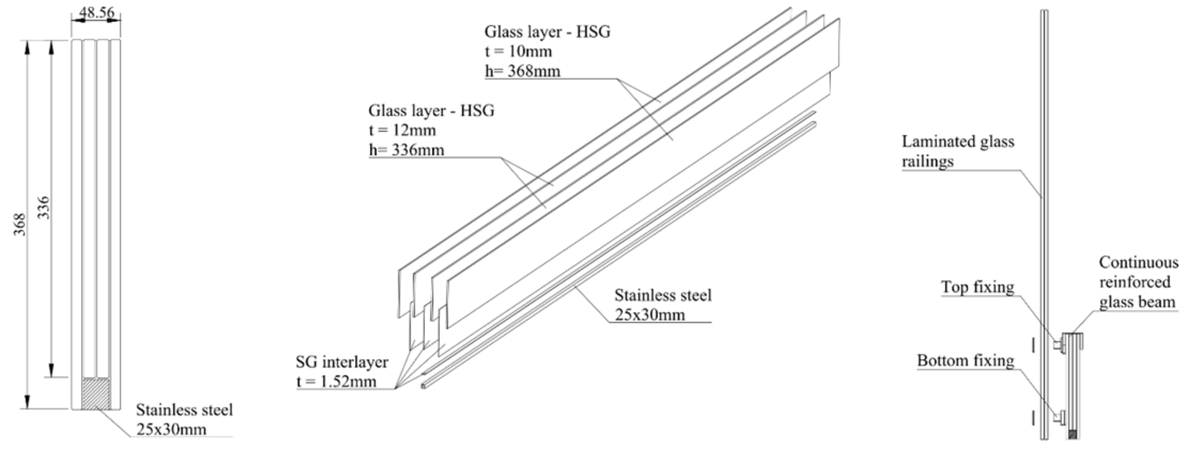


a) b)

Fig. 3a) Isometric view of the indoor footbridge, b) exploded view of the indoor footbridge.

2.1. Continuous steel-reinforced laminated glass beam

The steel-reinforced glass beam has a length of 5790 mm, a height of 368 mm and is 48.56 mm deep. It consists of 4 heat-strengthened glass layers, see figure 4a), the two external layers have a thickness of 10 mm and a height of 368 mm; the two inner layers have a thickness of 12 mm and a height of 336 mm; the stainless steel reinforcement has a rectangular cross-section of 30x25 mm and is located at the lower edge of the inner glass layers. The glass layers and the steel reinforcement are joined together by a SentryGlas® (SG) interlayer 1.52 mm thick, see figure 4b).



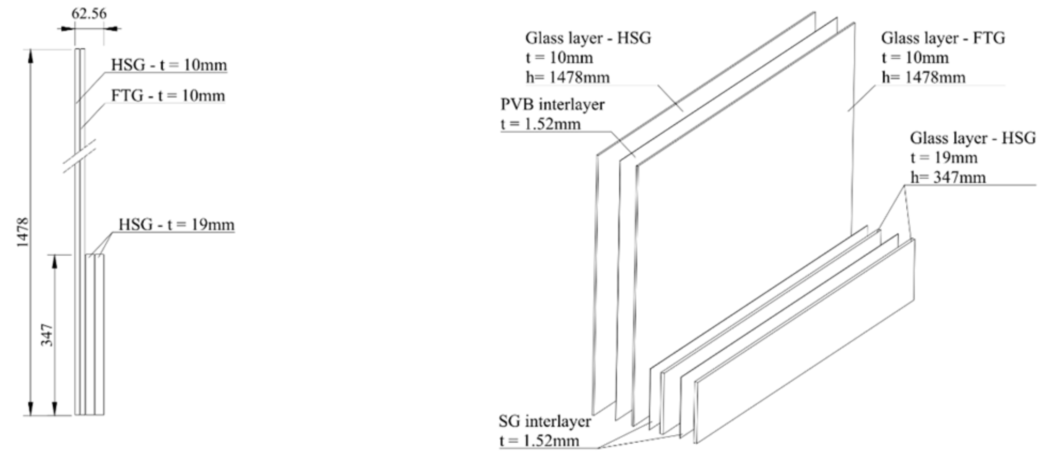
a) b) c)

Fig. 4a) Cross-section of the steel-reinforced laminated glass beam, b) exploded view of the steel-reinforced laminated glass beam, c) detail of the connection of the laminated glass railings to the steel-reinforced laminated glass beam.

A glass railing is connected to the 5790 mm glass beam, it has a height of 1500 mm and is made of three laminated glass panels. Each panel is joined to the outer lateral surface of the glass beam by glued and mechanical fixings, figure 4c). The bottom fixings are glued whereas the top fixings are mechanically fixed to a steel strip glued to the top edge of the beam. The laminated railings consists of two 12 mm thick glass layers joined together using 1.52 mm thick PVB interlayer. The outer glass layer is heat-strengthened whereas the inner glass layer is fully tempered.

2.2. Continuous laminated glass beam

The frontal part of the footbridge consists of three laminated glass beams. The lateral beams are 2130 mm long whereas the central one is 2135 mm long. The beams are made of 4 glass layers having thickness of 10 mm and 19 mm glued together using 1.52 mm thick PVB and SG interlayers, see figures 5a) and b). The two 19 mm thick glass layers have a height of 347 mm with the top edge as supporting surface of the glass deck. The 10 mm thick glass layers have height of 1478 mm and act as railings. All the glass layers are heat-strengthened with the exception of the inner 10 mm glass layer that is fully tempered glass.



a) b)

Fig. 5a) Cross-section of the continuous laminated glass beams, b) exploded view of the continuous laminated glass beams.

2.3. Laminated glass floor

The glass deck is made of three laminated glass panels, each consisting of three glass layers glued together by means of 1.52 mm PVB interlayer, see Table 1 for thickness and thermic treatment. The glass panels are plates simply supported along the edges, they are rectangular but have different sizes, 1760x2155 mm and 1760x2150 mm.

Table 1: Composition of the laminated glass floor.

Glass layer’s position	Thickness [mm]	Glass treatment
Top	8	FTG
Central	10	HSG
Bottom	8	FTG

3. Design

3.1. Loading

The indoor glass footbridge has been designed according to the Italian construction regulations NTC 2008 which give a characteristic value of 3.0 kN/m^2 as imposed vertical load on the floor, a characteristic value of 2.0 kN as concentrated vertical load on the floor, and a characteristic value of 1.0 kN/m as imposed horizontal load acting on the top edge of the railings.

As the paper focuses on the design of the steel-reinforced laminated glass beam only the ULS and SLS load combinations with the leading variable action 3.0 kN/m^2 are considered, see Table 2.

Table 2: Load combinations.

Load Combination	Load		Value	γ
ULS	Self-weight	G_1	--	1.3
	Permanent load	G_2	--	1.3
	Imposed load	q_k	3.0 kN/m^2	1.5
SLS	Self-weight	G_1	--	--
	Permanent load	G_2	--	--
	Imposed load	q_k	3.0 kN/m^2	--

3.2. Numerical models

In order to design the 5790 mm steel-reinforced laminated glass beam, two 3D numerical models have been created with the Strand7® Finite Element Software using solid continuum elements. In the first FE model the structural response of the beam only under the self-weight, the permanent load and the imposed load has been investigated. In this model the presence of the railings and their stiffness contribution has not been considered. The second numerical model takes into account the presence of the railings connected to the outer surface of the glass beam.

In both models glass has been modelled as a linear elastic brittle material responding linearly in tension and in compression with a Young’s modulus of 70 GPa and a Poisson’s ratio of 0.22. Stainless steel has been modelled as a linear-plastic material having a Young’s modulus of 210 GPa, a Poisson’s ratio of 0.33. In order to investigate the influences of the time dependent viscoelastic behaviour of the SG and PVB interlayers on the structural response of the beam, various values of the Young’s modulus and Poisson’s ratio have been considered in the numerical analyses. The SG and PVB interlayers have been assumed as linear elastic materials. The mechanical properties of the PVB interlayer have been determined according to Bennison et al. (1999) and Van Duser et al. (1999). Glass, steel and interlayers have been modelled using of 3D elements, the permanent and the imposed load have been uniformly applied to the top horizontal edge of the steel-reinforced laminated glass beam. The beam is simply supported at its ends by steel supports placed at a distance of 5545 mm from each other.

Table 3: Mechanical properties of the SG and PVB interlayer.

Interlayer	Temperature [°C]	Time	Young's modulus [MPa]	Poisson's ratio
SG 10°C – 1hr	10	1 hr	597	0.450
SG 20°C – 1hr	20	1 hr	493	0.459
SG 24°C – 1hr	24	1 hr	416	0.458
SG 24°C – 10yr	24	10 yr	129	0.489
SG 30°C – 1 hr	30	1 hr	178	0.485
PVB 20°C – 1hr	20	1 hr	2.52	0.498
PVB 24°C – 1hr	24	1 hr	1.65	0.498
PVB 24°C – 10yr	24	10 yr	0.15	0.498

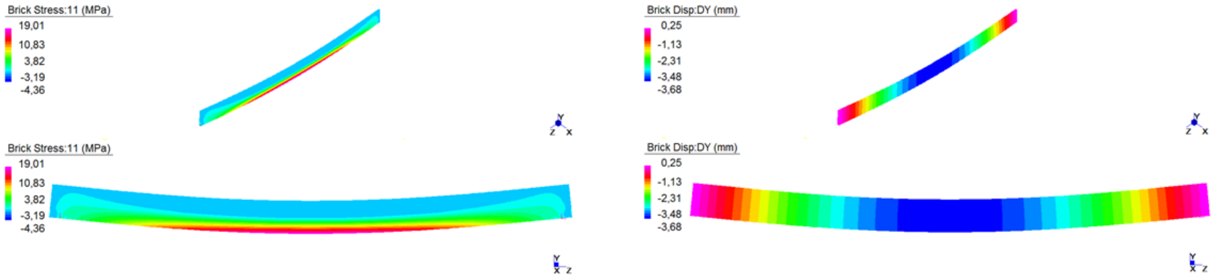
3.3. First FE model

Table 4 lists the maximum vertical displacement for the SLS load combination and the maximum values of the tensile and compressive stresses for the ULS load combination for various values of the mechanical properties of the SG interlayer. The maximum tensile and compressive stresses in glass and steel are always reached at the midsection of the beam, see figure 6a).

Table 4: Maximum values of stresses and vertical displacements

Model	ULS			SLS
	σ_g^+ [MPa]	σ_s^+ [MPa]	σ_g^- [MPa]	δ [mm]
SG 10°C – 1hr	19.00	56.84	-22.31	3.68
SG 20°C – 1hr	19.00	56.82	-22.32	3.68
SG 24°C – 1hr	19.01	56.80	-22.32	3.68
SG 24°C – 10yr	19.05	56.60	-22.35	3.69
SG 30°C – 1hr	19.08	56.45	-22.37	3.86

σ_g^+ = maximum tensile stress in glass at midpoint of the lower edge
σ_s^+ = maximum tensile stress in steel at midpoint of the lower edge of the reinforcement
σ_g^- = maximum compressive stress in glass at midpoint of the upper edge
δ = maximum vertical displacement



a) b)

Fig. 6a) Tensile stresses in glass for ULS combination (SG 24°C – 1 hr) and b) vertical displacement for SLS combination (SG 24°C – 1 hr).

3.4. Second FE model

Starting from the results of the first numerical model a more complete FE model of the structure has been developed, see figures 7a) and b). A 3D numerical model of half of the laminated glass beam and railings has been generated, for which three numerical analyses have been performed using three different values of the Young's modulus and Poisson's ratio for the SG and PVB interlayers.

Table 5 lists the maximum vertical displacement for the SLS load combination and the maximum values of the tensile and compressive stresses for the ULS load combination for various values of the mechanical properties of the SG and PVB interlayer. The presence of the glass railings reduces the vertical deformability of the glass beam and its tensile stresses at the lower edge of the glass layers.

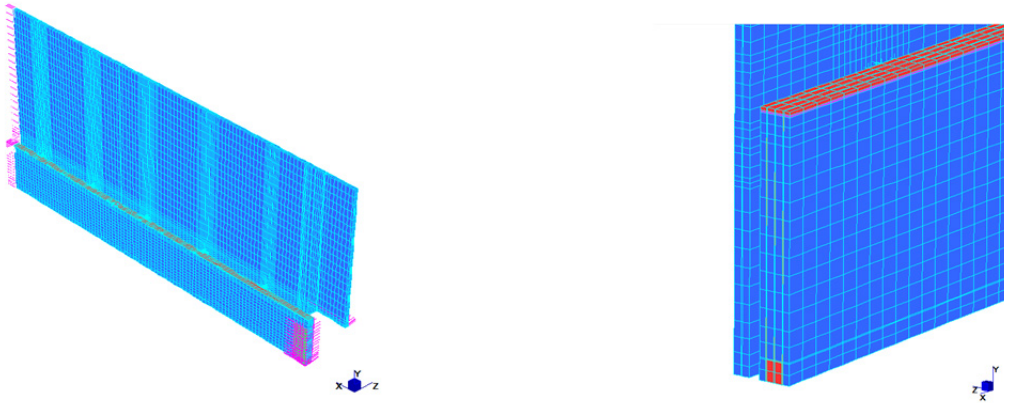

a) b)

Fig. 7a) Isometric view and b) detail of the mid cross-section of the beam and railings in the second FE model.

Table 5: Maximum values of stresses and vertical displacement.

Model	Interlayer		ULS			SLS
	SG	PVB	σ_g^+ [MPa]	σ_s^+ [MPa]	σ_g^- [MPa]	δ [mm]
20°C – 1hr	SG 20°C – 1hr	PVB 20°C – 1hr	9.96	28.20	-12.52	1.69
24°C – 1hr	SG 24°C – 1hr	PVB 24°C – 1hr	10.00	28.28	-12.58	1.70
24°C – 10yr	SG 24°C – 10yr	PVB 24°C – 10yr	10.06	28.17	-12.67	1.72

σ_g^+ = maximum tensile stress in glass at midpoint of the lower edge
σ_s^+ = maximum tensile stress in steel at midpoint of the lower edge of the reinforcement
σ_g^- = maximum compressive stress in glass at midpoint of the upper edge
δ = maximum vertical displacement

3.5. Analytical model

In order to validate the first numerical model, the tensile stresses at the lower edge of the glass layers and the maximum deflection of the simply supported steel reinforcement laminated glass beam have been determined by using an analytical model. The analytical model has been developed by Louter to design and check this kind of glass beams in analogy with reinforced concrete (Louter 2011) (Louter et al. 2012).

Table 6 lists the calculated maximum vertical displacement for the SLS load combination and the maximum values of the tensile and compressive stresses in the glass layers and in the steel reinforcement for the ULS load combination. The maximum value of stresses are reached at the midsection of the beam.

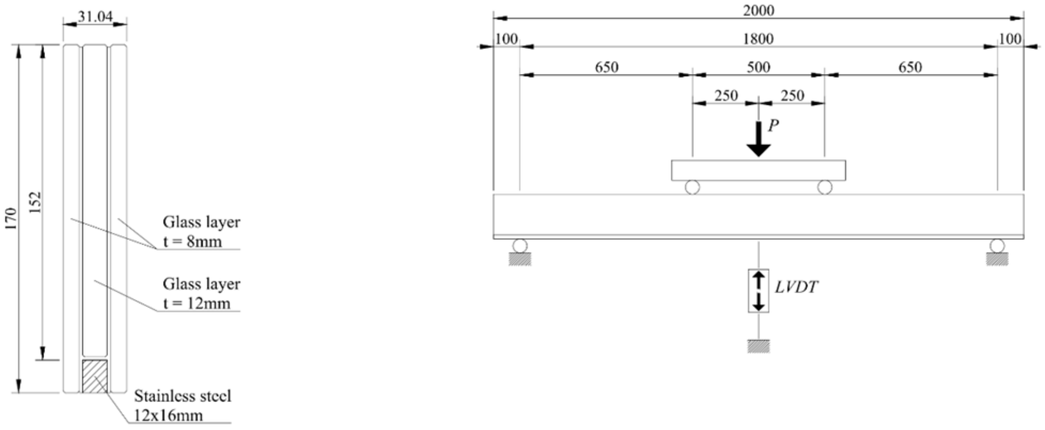
Table 6: Maximum values of stresses and vertical displacement calculated with the analytical model.

Model	ULS			SLS
	σ_g^+ [MPa]	σ_s^+ [MPa]	σ_g^- [MPa]	δ [mm]
Analytical	18.86	56.67	-22.13	3.60

σ_g^+ = maximum tensile stress in glass at midpoint of the lower edge
σ_s^+ = maximum tensile stress in steel at midpoint of the lower edge of the reinforcement
σ_g^- = maximum compressive stress in glass at midpoint of the upper edge
δ = maximum vertical displacement

A series of laboratory tests have been performed at the University of Pisa on 6 specimens of 2000 mm long continuous steel reinforcement laminated glass beams, see figure 8a) and Table 7. Four point-bending tests have been performed increasing the load up to the complete collapse of all the glass layers, see figure 8b).

Strain gages were applied on steel and glass at tensile edge and on the lateral surface of glass. LVDTs were arranged to measure the vertical displacement during the test.



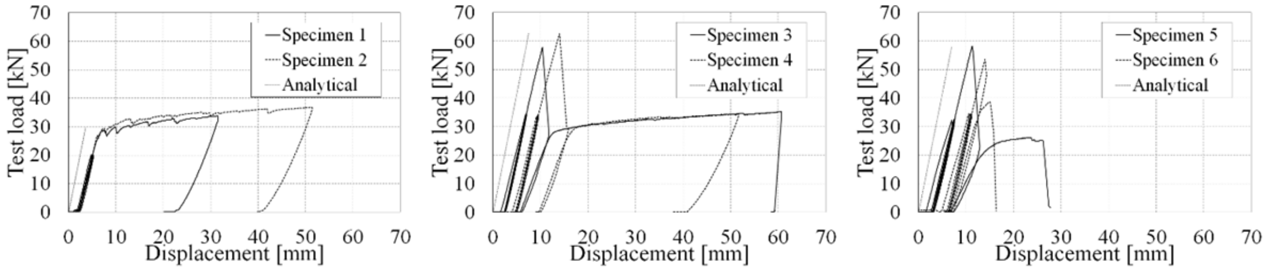
a) b)

Fig. 8a) Cross-section of the laminated glass beams experimentally investigated, b) schematic view of the test setup.

Table 7: Steel-reinforced glass beams experimentally investigated.

Specimen	Length [mm]	Height [mm]	Glass thickness [mm]	Glass	Interlayer	Stainless steel cross section [mm]
Specimen 1	2000	170	8-12-8	Annealed	SG	12x16
Specimen 2	2000	170	8-12-8	Annealed	SG	12x16
Specimen 3	2000	170	8-12-8	Heat strengthened	SG	12x16
Specimen 4	2000	170	8-12-8	Heat strengthened	SG	12x16
Specimen 5	2000	170	8-12-8	Heat strengthened	DG41	12x16
Specimen 6	2000	170	8-12-8	Heat strengthened	DG41	12x16

The results of the laboratory test confirmed the results obtained by the analytical model (Louter 2011) (Louter et al. 2012). Figures 9a), b) and c) show the test load – vertical displacement diagrams and compare the experimental results with the analytical uncracked results. The slope of the uncracked branches of both the analytical and the experimental diagrams are identical.



a) b) c)

Fig. 9a), b) and c) Test load – maximum vertical displacement diagrams.

4. Structural load testing

4.1. Description

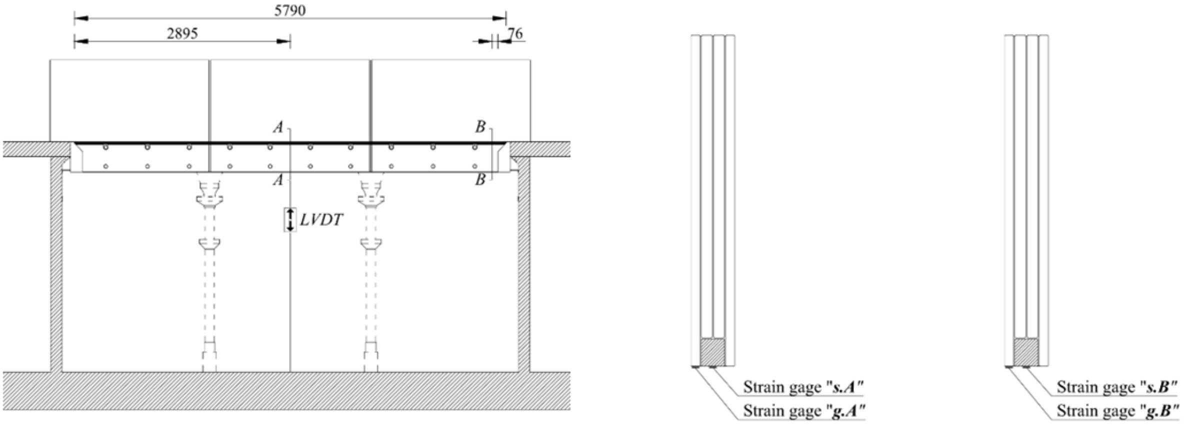
The load testing of the indoor footbridge has been performed by loading the glass floor with a uniformly increasing load, see figures 10a) and b). The load has been increased from 0.0 up the final value of 3.0 kN/m^2 in steps of 0.5 kN/m^2 by progressively filling with water a rectangular tank of 5700x1600 mm. The test was performed at room temperature, RT +21°C.

a) b)

Fig. 10a) and b) The structure during the load testing.

Strain gages were applied on steel and glass at the lower edge of the 5790 mm steel-reinforced glass beam, to the lower edges of the central laminated glass beam and to the midpoints of the laminated glass horizontal plates. Three linear variable differential transformers – LVDTs – were arranged to measure the vertical displacement of the midpoint of the lower edge of the steel-reinforced glass beam, the midpoint of the lower edge of the central laminated glass beam and the midpoint of the central glass plate. Figures 11a), b) and c) show the position of the LVDT and the position of the strain gages on the beam.

Thanks to a data acquisition board it has been possible to record the values of the test load applied, the vertical displacement of LVDTs and the elongation of all the strain gages.



a) b) c)

Fig. 11a) Position of the LVDT and position of the strain gages on the beam, b) Cross-section A-A, c) Cross-section B-B.

4.2. Results

Table 8 lists the tensile stresses and the vertical displacement of the reinforced glass beam obtained by the load testing. The reported values of the tensile stresses are obtained by assuming a Young's modulus of 70 GPa for glass and of 210 GPa for steel.

Table 8: Stresses and vertical displacement obtained during the load testing.

Time [min]	Load [kN/m^2]	$\sigma_{g.A}^{+}$ [MPa]	$\sigma_{s.A}^{+}$ [MPa]	$\sigma_{g.B}^{+}$ [MPa]	$\sigma_{s.B}^{+}$ [MPa]	δ_A [mm]
0	0.00	0.00	0.00	0.00	0.00	0.0
21	0.25	0.53	1.49	0.06	0.17	0.2
42	0.50	1.02	2.98	0.12	0.36	0.5
68	1.00	2.25	6.36	0.34	0.84	0.7
92	1.50	3.52	10.00	0.59	1.41	1.3
117	2.00	4.85	13.52	0.85	1.95	1.9
143	2.50	6.24	17.28	1.13	2.63	2.3
168	3.00	7.79	21.36	1.42	3.36	2.9
198	3.00	7.83	21.21	1.45	3.34	3.0
298	0.00	0.09	-0.71	0.07	-0.84	0.4
308	0.00	0.12	-0.71	0.05	-0.92	0.4

σ_g^{+} = tensile stress at the tensile edge of the glass layer
σ_s^{+} = tensile stress in steel reinforcement
δ = vertical displacement

A numerical analysis has been performed in order to check and validate the second numerical model. The mechanical properties of the SG and PVB interlayers have been chosen according to the room temperature and the duration of the load testing, T=20°C – t=1hr. In the numerical model the beam has been loaded with the exact value used for the actual testing.

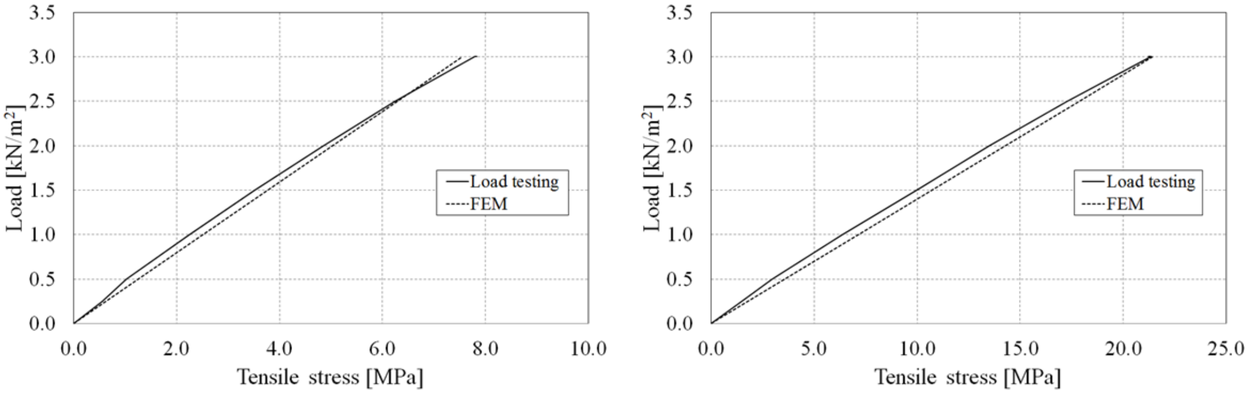
Table 9 lists the stresses in glass and steel obtained from the numerical analysis at the tensile edge of the sections A-A and B-B, and it provides also the vertical displacement of the section A-A.

Table 9: Vertical displacement and stresses obtained from the numerical analysis.

Load [kN/m^2]	$\sigma_{g.A}^{+}$ [MPa]	$\sigma_{s.A}^{+}$ [MPa]	$\sigma_{g.B}^{+}$ [MPa]	$\sigma_{s.B}^{+}$ [MPa]	δ_A [mm]
0.00	0.00	0.00	0.00	0.00	0.0
1.00	2.51	7.15	0.40	1.11	0.72
2.00	5.03	14.30	0.80	2.23	1.44
2.50	6.29	17.87	1.00	2.79	1.80
3.00	7.55	21.45	1.21	3.35	2.16

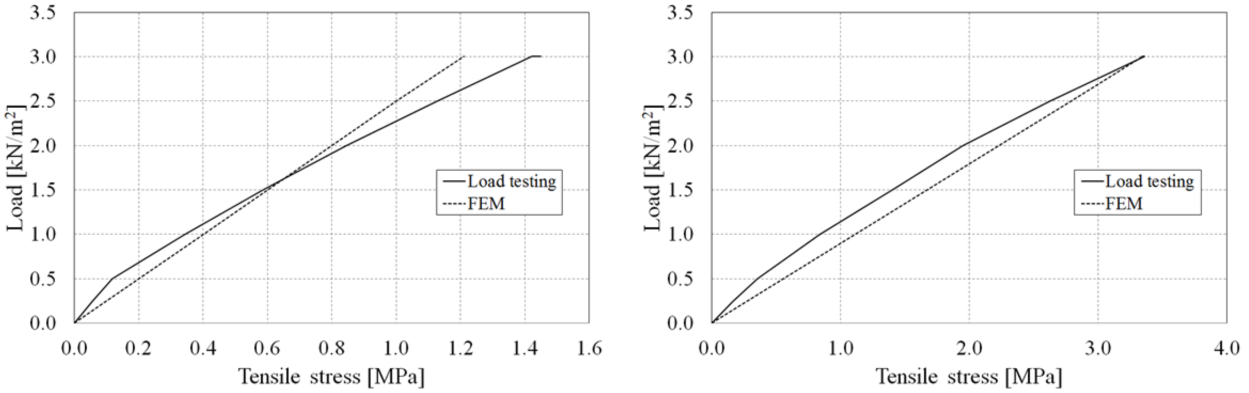
σ_g^{+} = tensile stress at the tensile edge of the glass layer
σ_s^{+} = tensile stress in steel reinforcement
δ = vertical displacement

Figures 12 and 13 show a graphical comparison of the tensile stresses in the steel reinforcement and in the glass obtained by the load testing and the numerical model.



a) b)

Fig. 12 Comparison of the measured and FEM tensile stress a) $\sigma_{g.A}^{+}$ in glass at section A-A and b) $\sigma_{s.A}^{+}$ in steel at section A-A.



a) b)

Fig. 13 Comparison of the measured and FEM tensile stress a) $\sigma_{g.B}^{+}$ in glass at section B-B and b) $\sigma_{s.B}^{+}$ in steel at section B-B.

Figure 14 shows a graphical comparison of vertical displacement of the beam at midpoint obtained by the load testing and by the numerical model.

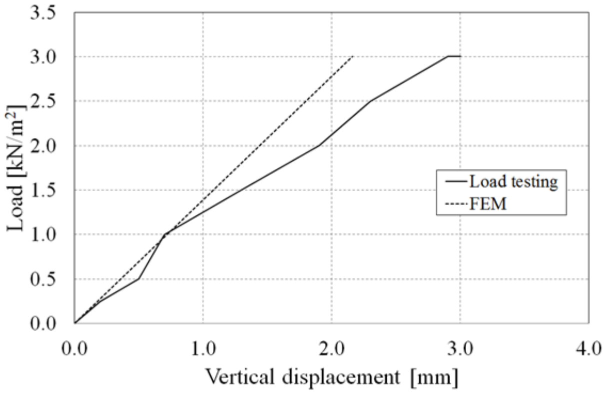


Fig. 14 Comparison of the measured and FEM vertical displacement of the section A-A.

5. Conclusions

The glass footbridge built inside a refurbished masonry building of the 19th century public slaughterhouse of Pisa has been an important opportunity to design a 5790 mm long steel-reinforced laminated glass beam using both numerical and analytical modellings and to check and compare profitably these findings with the results obtained by the load testing.

Analytical models are powerful and helpful tools for the pre-design process and for checking the results of complex numerical models. For a more accurate evaluation of the real structural response of the beam, 3D numerical analyses are necessary to take into account exactly the mechanical properties of the interlayer.

The numerical results of the first 3D model and the analytical results give almost matching results. The values of the stresses obtained from the first numerical model differ from the analytical one by less than 1%, and the deformations differ by 7%.

The second numerical model of the beam with the railings provides results that are comparable with the testing results. This numerical model does not take into account all the parameters that influence the real response of the footbridge such as the friction or the exact value of the stiffness of the glued connection, but allows a more precise design of the structure. By comparing the testing results and the numerical results it is possible to see that the values of the stresses are accurate; the difference of vertical deformation obtained are probably due to sliding or non-linear motion that the numerical model neglects.

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