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Proposal for a variable stiffness movable footbridge over Canale Burlamacca in Viareggio: design and analysis

The paper illustrates the project for a movable footbridge for pedestrians and cyclists in the Viareggio docks district. The project study contemplates an asymmetric cable stayed structure with the positioning of a single tower (mast) exactly on the rotation center of the entire system. The attempt to minimize the deck structural thickness and the contemporary limited width of the quay underlying the footbridge in its opened position brought to the decision to create a structure able to vary its stiffness according to the current static scheme. Hence, at the beginning of the opening phase, while swapping from a simply supported beam scheme to a cantilever scheme, the side bands of the footbridge (wings) fold up increasing considerably the global structural stiffness and at the same time, allowing for a remarkable reduction of the transversal section width. From an aesthetic and technological point of view the bridge draws inspiration directly from the sailing boats.

Proposta per una passerella ciclo-pedonale mobile a spessore variabile sul Canale Burlamacca a Viareggio. Progetto e analisi

L'articolo illustra il progetto per una passerella ciclo-pedonale mobile sul Canale Burlamacca a Viareggio. Il ponte, che dovrebbe sostituire l'obsoleto manufatto attualmente in servizio, è situato tra l'area delle Darsene e il lungomare cittadino. La soluzione in oggetto, premiata con una menzione per l'originalità delle soluzioni previste al concorso di progettazione bandito dal Comune di Viareggio, è caratterizzata dall'adozione di un'inedita e originale soluzione girevole. La limitata larghezza della banchina e il tentativo di minimizzare lo spessore dell'impalcato hanno portato alla decisione di creare una struttura in grado di variare la propria rigidezza in accordo con lo schema statico corrente. Così, all'inizio della fase di apertura, nel passaggio da uno schema di trave semplicemente appoggiata a quello di trave a sbalzo, le parti laterali dell'impalcato (ali) si piegano verso l'alto aumentando considerevolmente l'inerzia flessionale del manufatto e riducendone contestualmente l'ingombro trasversale. Ciò permette di contenere lo spessore dell'impalcato in 45 cm su una luce di 24 metri. L'analisi dinamica effettuata assicura l'assenza di fenomeni vibrazionali indesiderati.

The project for a new movable footbridge over the Burlamacca Canal in Viareggio stems as a result of a design competition banned by the City Council in 2001. This was due to the necessity of replacing the existing bridge, old and inadequate, with a new one, at the beginning of the renovated "Passeggiata a mare" (sea promenade), designed by Sir Richard Rogers. Viareggio sea promenade, during the summer, is one of the most attended and renowned walks of the whole Tirrenian sea.

Therefore, the function attributed to the new cycle and pedestrian movable bridge is then to act as a landmark for the traditional beginning of the Passeggiata itself and actually to extend it, giving direct and effective connection to the city docks, on the other side of the Canal, to the south. The intense transit of sailing boats required the design of a movable structure: this was achieved by mean of a swinging bridge designed on an overall span of 24 meters. For this purposes the new projects foresees:

1- a new and larger width for the footbridge deck, sized on today's pedestrians and cyclists flow. The appropriate breadth was then estimated to be the one able to lodge the two 1.25m lanes of the cycle path and a footpath with a minimum width of 3.5m;
2- the search for an aesthetic based on the maximum lightness. This was achieved reducing dramatically the deck thickness and adopting technologies and solutions directly withdrew from the sailing-boats world; this was justified by the adjacent presence of the docks;
3- the conception of a place thought as a lay-by area and a meeting point, rather than a mere crossing device; for this reason the bridge deck is shaped with a central widened part, in order to

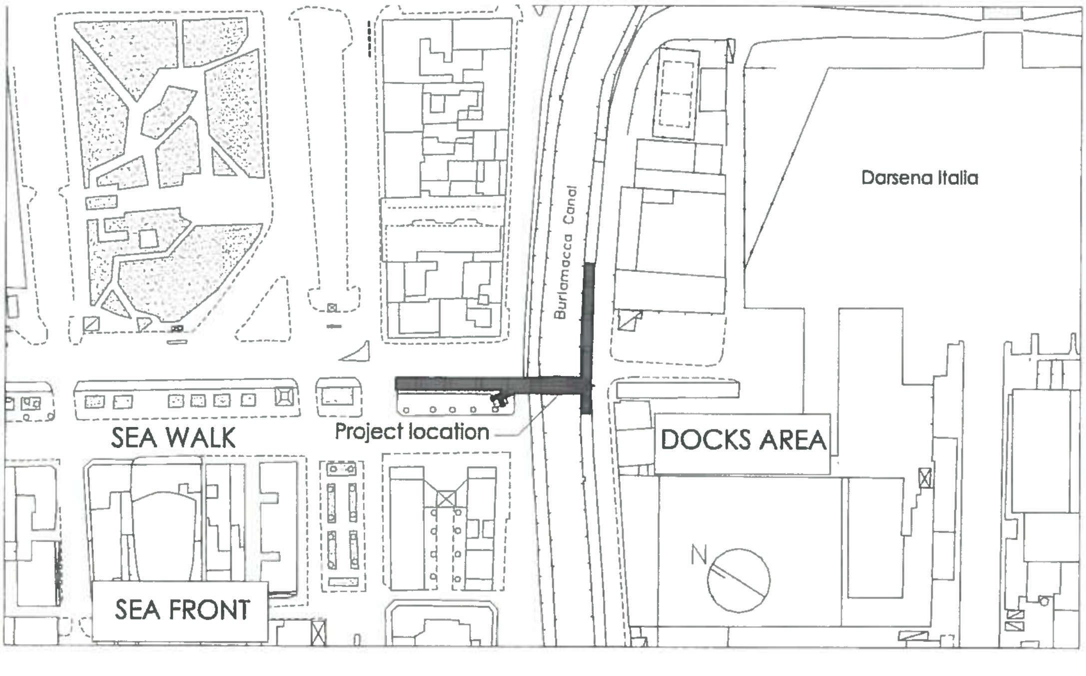


Fig. 1 Key-plan

create a real “on water space” which can be used and rigged for different events according to different needs;

4- the choice of an adequate structural typology able to cope with the technical and durability standards;

5- a solution which takes into account the future scenario contemplated by the Roger’s project with no interference with the actual traffic flows.

THE PROJECT

On the base of what previously mentioned a cable stayed cantilever swinging footbridge was thought as the most matching solution. The different boundary conditions on the two different quays and the limited total span, suggested the adoption of a non symmetrical solution for this typology, with a single must placed on the docks side. The whole structure results to be self-anchored thanks to a vertically balanced scheme which exploits the presence of a disguised concrete block (placed south of the mast on the shorter arm) which takes back the gravity center to two meters (north of the must on the side of the longer arm spanning the canal) from the rotation center. The footbridge has a steel deck composed by wide flange sections and hollow rectangle sections welded together. The section adopted will be specified afterwards. The total structural weight is slightly under 1.2 kN/m2. The deck section has a structural thickness of 0.45 m, which is rather slender if compared to the usual sections of movable cantilever footbridges on similar spans.

This is due to the cable stayed static scheme adopted and to a couple of movable lateral bands (wings) which can rotate from an horizontal position to an almost vertical one, varying dramatically the overall structural stiffness. This device turns up to be very useful also in containing the deck width during the opening phase, so that the transverse section does not exceed the quay breadth. The static scheme variation between the two phases of opening and closure, namely the swapping from a continuous beam (on 4 supports, with the two central acting as springs) to a cantilever beam, leaded to the conception of a structure able to vary its stiffness according to the current restraint conditions. Thus, the two lateral wings, just before the beginning of the closure phase, fold upward pushed by a system of hydraulic jacks. This results in a consequent appreciable increase of the cross section moment of inertia, which allows, with the help of the stays, to limit the maximum deflection, otherwise unacceptable.

In this way, the deck width, which is dimensioned according to the estimated flows of pedestrians and

Fig. 2 Day and night view

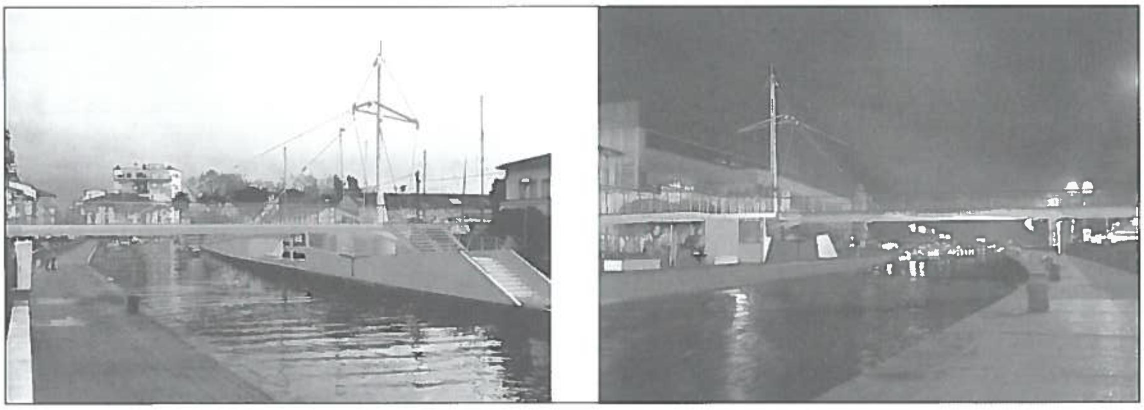
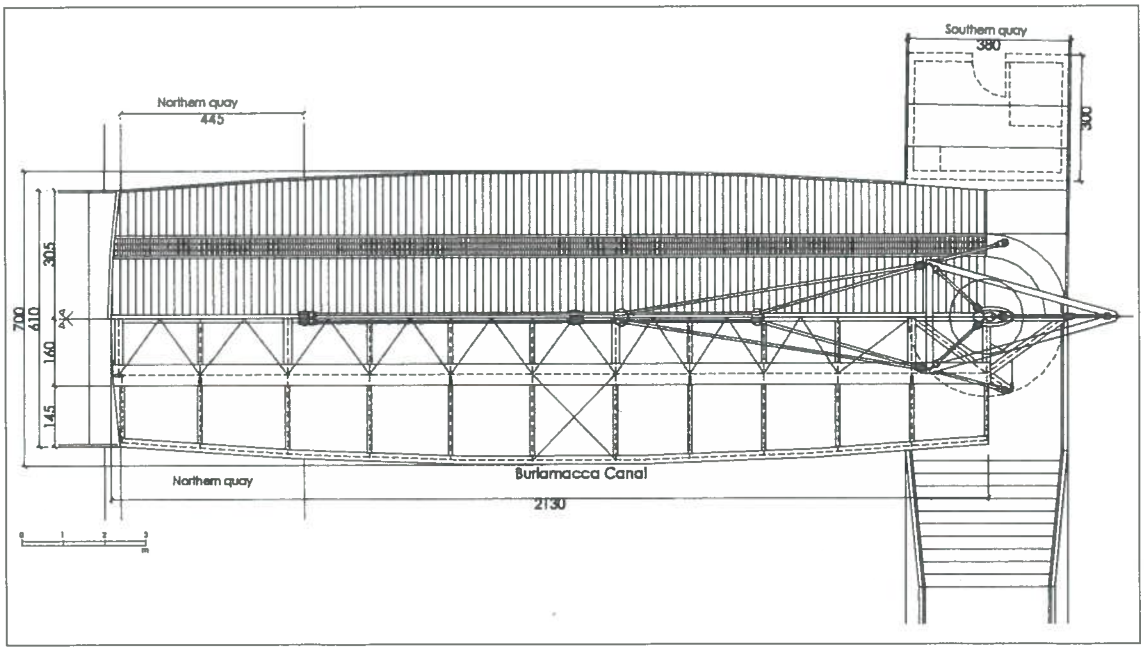


Fig. 3 Plan view



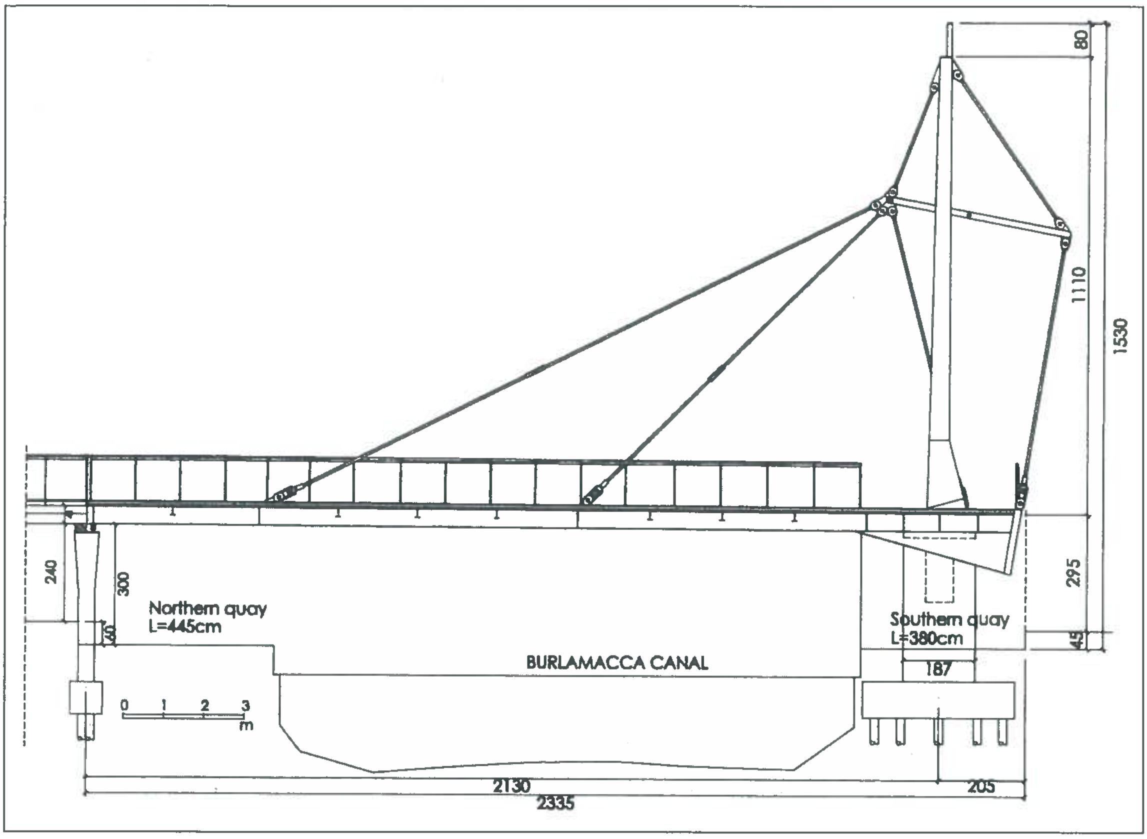


Fig.4 Longitudinal section

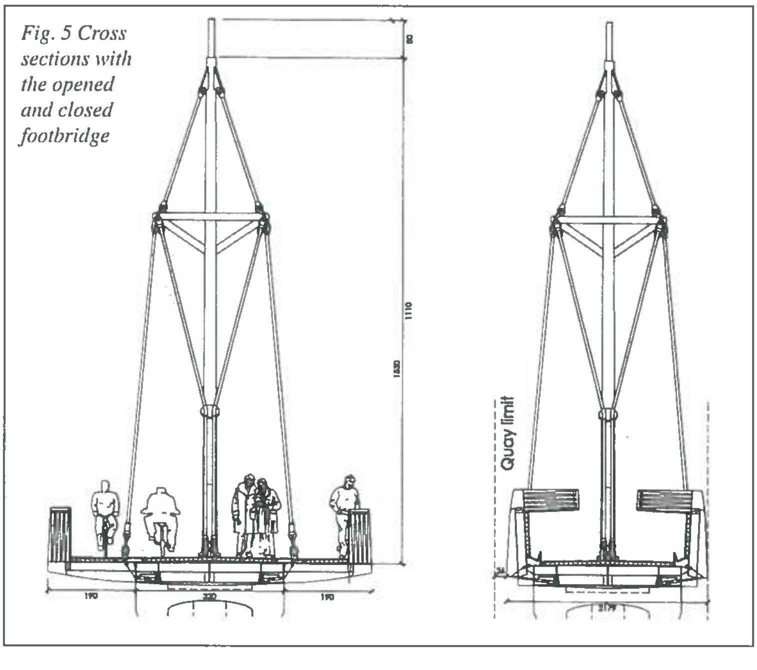


Fig. 5 Cross sections with the opened and closed footbridge

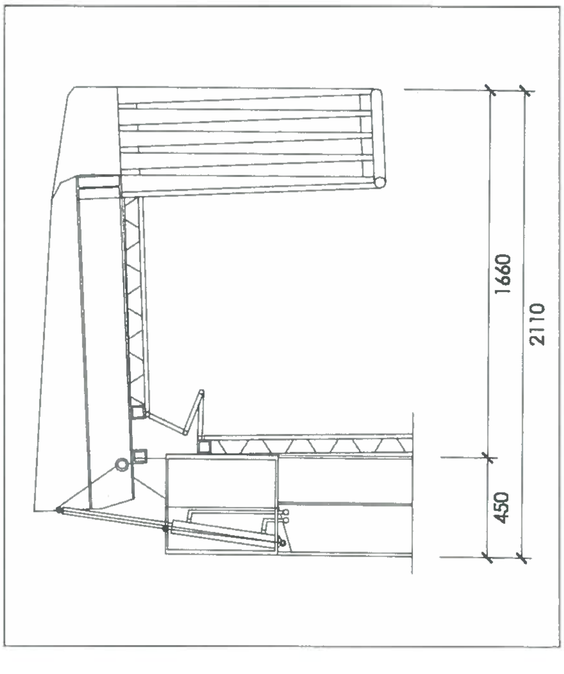


Fig. 6 Hinge detail

cyclists, can rest exactly above the quay during the closure phase, with no section reduction for the adjacent street and canal, which would be considered as an unbearable danger both for the cars and for the boats.

The deck structure can bear its self-weight also without stays. This makes possible an easy maintenance and substitution of the stays. All maintenance must be performed with no accidental loads applied on the deck and with the bridge not accessible to public.

After the new stays are positioned, they must be pre-tensioned so that no permanent deflection is given to the deck under dead loads.

OPENING PHASES

The swinging phases with the related times can be summarized as follows:

a) The security shear pins, both of the footbridge and of the southern access stair are hydraulically unlocked (see hydraulic scheme in fig. 9). Afterwards, the lateral wing starts to fold upward and contemporary the southern staircase lowers. This first phase needs an estimated time of 36" to be completed.

b) The footbridge swings to the complete closure powered by a 50 cc engine (with a break able to develop a static torque of 290 Nm and a dynamic torque of 190 Nm at 1200 min-1) which as-

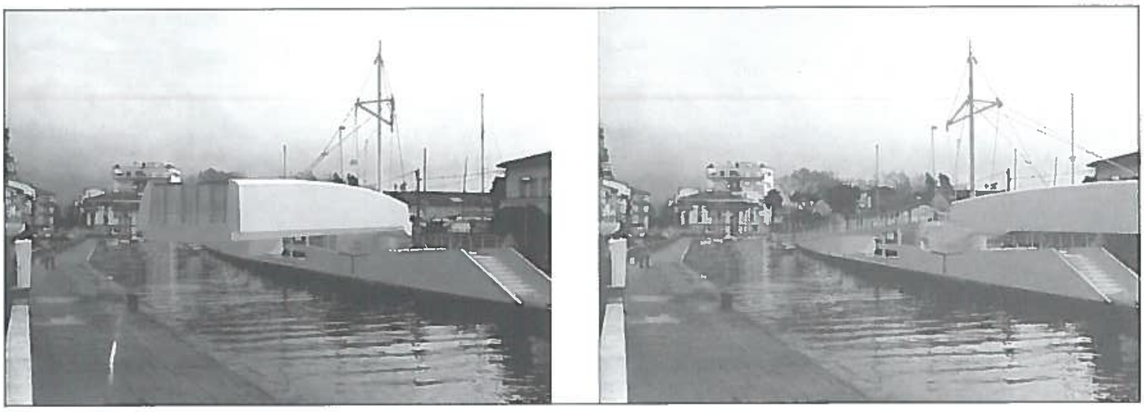


Fig. 7 Opening phases

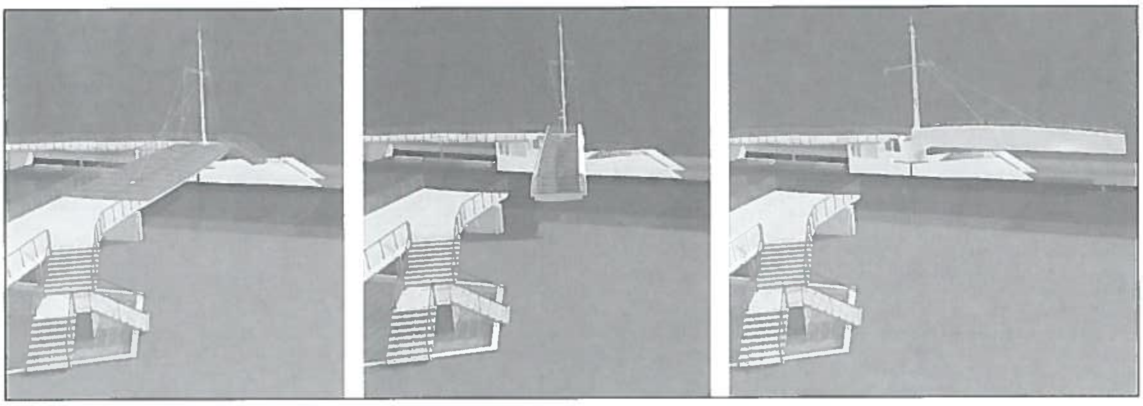


Fig. 8 Renders

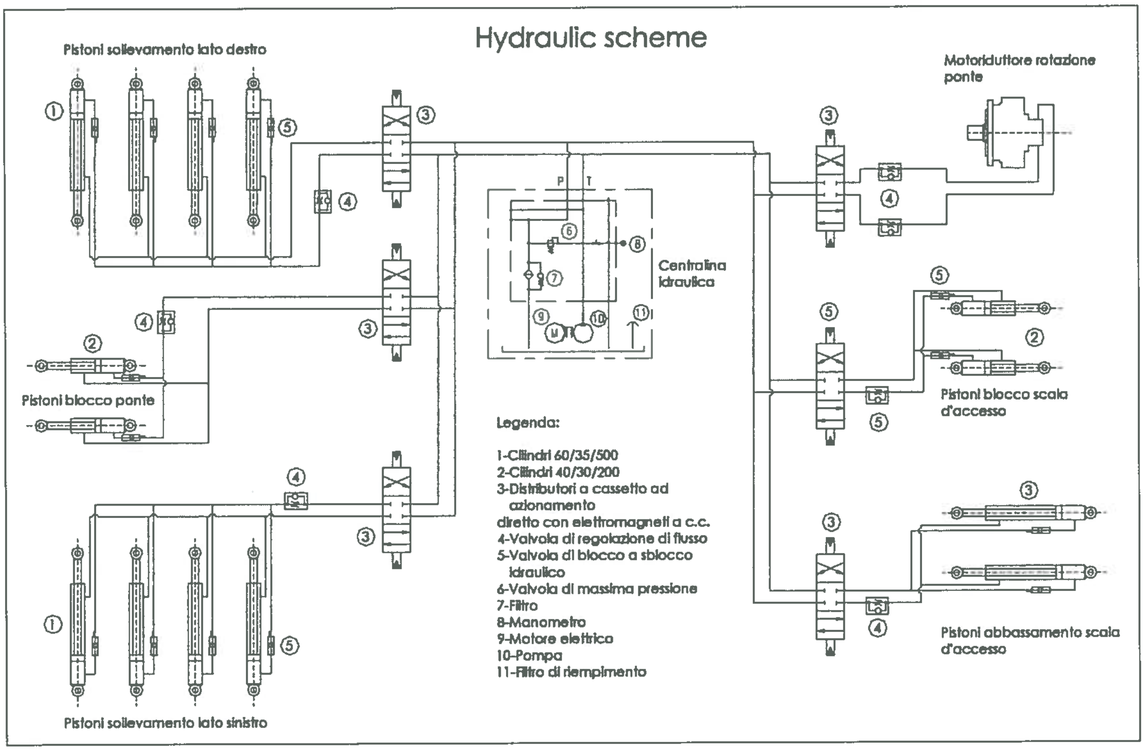


Fig. 9 Hydraulic scheme (All the motion devices were designed by dr eng. Francesco Cavarzerani)

sures the completion of this phase in approximately 120".

STRUCTURAL BEHAVIOUR

The structural analysis, both in the opening phase and with the closed bridge (i.e. not accessible to public), were performed through a FEM modeling (the chosen software is Straus 7). A three dimensional model was implemented with the use of beam and shell elements. The stays behaviour (considered as cable elements) was taken into account performing non linear analysis. Two structural conditions were implemented. The first one simulates the footbridge in the opened condition, with the static scheme of continuous beam. The second one concerns the closure phase and therefore schematizes the structure as a cantilever beam. In this second case the deck is characterized by a considerably increased stiffness thanks to the lateral wings which are folded upwards. One of the major problems affecting the structural behaviour of foot-

bridges is their dynamic behaviour. Slenderness causes structural vibrations which turn out to be very uncomfortable for all users. Recent and well known examples like the case of Millennium Bridge in London or the case of Solferino footbridge in Paris, temporary closed just after their inauguration, makes us aware of the risks that a very flexible structure implies. As a consequence, modal analysis were performed on this footbridge in order to estimate its dynamic behaviour preventing resonance phenomena.
The load analysis is listed in Table 1.

Design check in the most stressed sections

Deck beams. In table 2, some figures related to the highest stress values in the deck sections (due to relative axial force and bending moment) are listed.

Stays. The stays (Φ66), slightly pre-stressed, are subjected to the following tensile forces:

$N_{max,op}$ = 230.3 kN opened condition
$N_{max,cl}$ = 364.1 kN closed condition

These figures, compared with a braking load ($P_{r,min}$) of 3780 kN per stay, give a safety factor of $\tilde{a}_u \approx 10$. This high value is due to the need of achieving an appreciable axial stiffness of the stays.

Mast. The mast, above the deck, is characterized by an elliptical steel hollow section which varies its dimensions with the height. The mast is connected through the deck to the thrust bearing, which lays on a basement composed by a circular hollow section, with an external diameter of 1800mm, connecting the structure with its foundation. The maximum stresses on the two parts of the must (above and under the deck) are:

lower part (Φ1800):
$\sigma_{max,cl}$ = 56.48 MPa; $\sigma_{max,op}$ = 49.06 MPa
upper part (variable elliptical section):
$\sigma_{max,cl}$ = 56.75 MPa; $\sigma_{max,op}$ = 24.29 MPa

Foundations. Table 3 reports the loads on foundations.
Since reliable data on soil bearing capacity were not available, the following foundations were designed on the base of previous experiences:
1) South quay (docks side): for this foundation, a

Table 1 Load analysis

Dead loads:	
• structural self weight:	1.20 kN/m²
• paving (corrugated sheet and wood planks)	0.40 kN/m²
• steel mast	90.00 kN
• concrete counterbalance	260.00 kN
Accidental loads:	
• crowd	4.00 kN/m²

Table 2 Structural results on deck beams

	Closed footbridge			**Opened footbridge**		
	N [kN]	**M [kNm]**	**σ [MPa]**	**N [kN]**	**M [kNm]**	**σ [MPa]**
Longitudinal box beams	25.13	418.00	91.74	19.37	15.22	10.17
Longitudinal beams HEB 200	2.75	41.22	73.07	146.60	122.90	22.57
Longitudinal beams IPE 450	0.97	105.30	70.30	10.17	11.73	16.55
Central transverse beams IPE 450	0.88	93.04	63.01	2.18	17.13	12.39
Central transverse beams IPE 220	0.87	6.29	25.37	3.81	1.60	7.61
Lateral transverse beams IPE 200	0.21	16.11	83.03	14.22	0.53	9.64

Table 3 Loads on foundations

	Closed footbridge		**Opened footbridge**	
	N [kN]	**M [kNm]**	**N [kN]**	**M [kNm]**
Docks side	898	1981	532	1750
Sea-walk side	237	\	\	\

Table 4 Structural maximum deflections

	Maximum vertical deck deflection [mm]
Closed footbridge	45
Opened footbridge	38

Table 5 Materials

Foundations	**Piers**	**Deck**	**Mast**	**Stays (Φ66)**
concrete f_{ck} ≥20 MPa	concrete f_{ck} ≥25 MPa	steel beams f_{yk} ≥235 MPa	steel hollow section f_{yk} ≥235 MPa	$P_{r,min}$ = 3780 kN
steel for reinforc. f_{yk} ≥430 MPa f_{tk} ≥ 540 MPa	steel for reinforc. f_{yk} ≥430 MPa f_{tk} ≥ 540 MPa	pins f_{yk} ≥355 MPa	steel base f_{yk} ≥235 MPa	

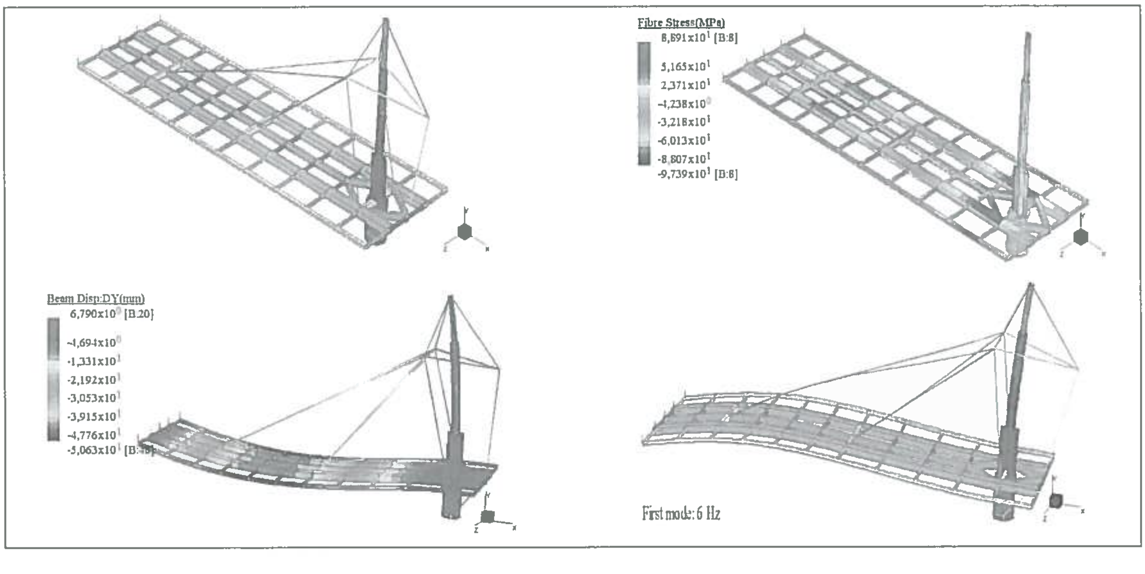


Fig. 10 Some structural analysis results. Opened phase

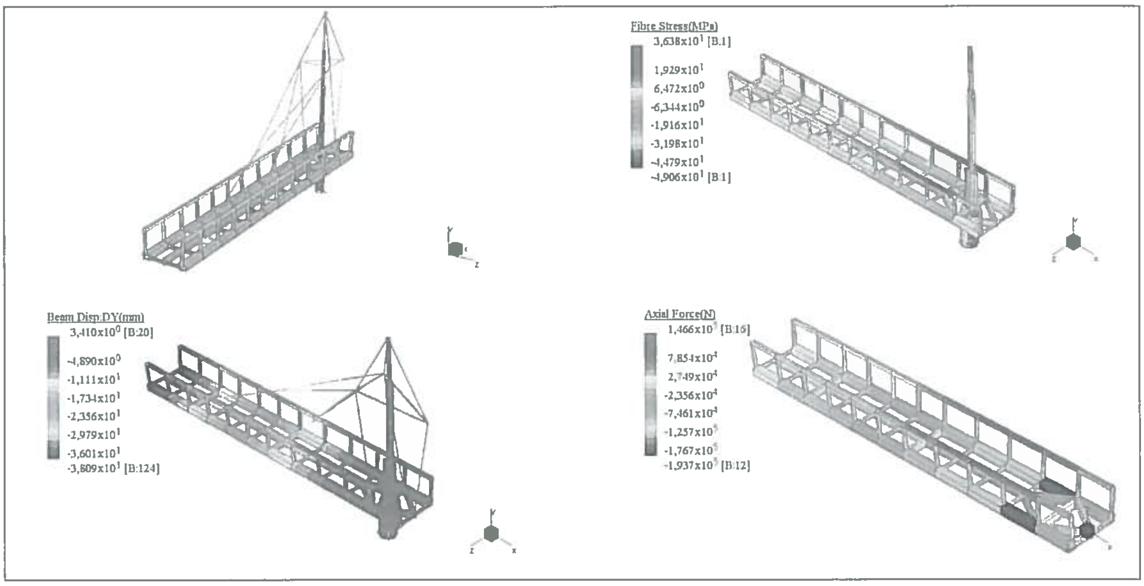


Fig. 11 Some structural analysis results. Closed phase

3.8 x 3.8 x 0.9 m plinth resting on 12 Φ200 micropiles was designed. The estimated ultimate load for each pile was $N_u = 260$ kN.

2) North quay (sea-walk side): for this foundation, a 5.15 x 0.8 x 0.8 m beam resting on 4 Φ200 micropiles was designed. The estimated ultimate load for each pile was $N_u = 260$ kN.

Deflections. Table 4 reports the maximum structural deflections of the deck both with the closed and the opened footbridge.

Natural frequencies. The structural natural frequencies are far from the characteristic value induced by the walking people, estimated to be around 2Hz. The first mode of the footbridge has a frequency of 6Hz.

Materials. See Table 5.

CONCLUSIONS

This kind of design, oriented towards a "global quality" of the project, was considered of primal importance from the beginning, in order to give a contribution able to improve the quality of the surrounding environment.

Designing on a small and medium scale requires the same commitment and carefulness that a large scale project necessitates. In fact, being the small scale the most common and diffused, a trivial design not aware of its social implication would turn out to be a missed occasion if not a damage for the collectivity. The adopted design solution seems to match all the requirements and needs of the project area in terms of serviceability, safety, aesthetics and costs.

This project was considered as structurally and aesthetically innovative and therefore awarded with a special mention by the jury.

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