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Retrofitting and Reinforcement of a Wire Suspended Bridge in Portugal

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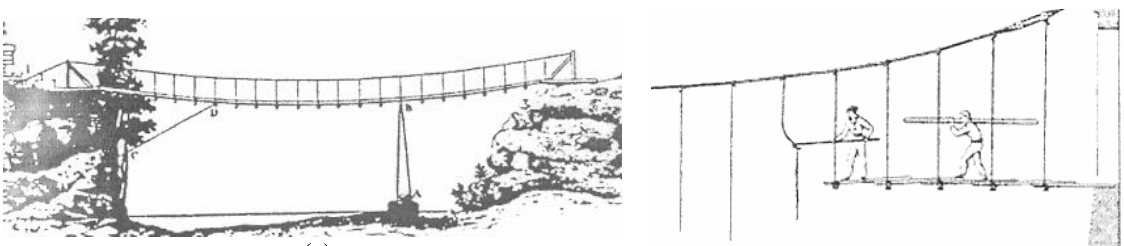
ABSTRACT: This paper presents a study made on a particular structure, a pedestrian wire bridge. It describes the work performed by the Nucleus for the Conservation and Rehabilitation of Buildings and Built Heritage (NCREP) of the Faculty of Engineering of University of Porto (FEUP) to respond to the interest of the Association of Municipals of Baixo Tâmega in retrofitting that peculiar bridge located at the North of Portugal. After a brief introduction and illustrating some examples of these type of structures built in Portugal, the paper describes the intervention methodology, which involved *in-situ* inspections and a large experimental campaign for the material and structural characterisation of the bridge. These studies were carried out with the contribution of mechanical and metallurgical specialists and allowed fitting the mechanical properties that were used in the numerical model for the simulation of the bridge

1 INTRODUCTION

The designation of Wire Bridge suggests a fragile and flexible structure. In this paper this designation will be referred to pedestrian suspended (by wires) bridges, with wooden flexible decks and, therefore, with relatively small frequencies of vibration. Originally this denomination was used because the cables were build using wires that were grouped *in situ*.

Wire bridges were constructed at different places in the world. The construction of the first bridge took place in the USA in 1816 (Denenberg 2005) but it didn't survive too long. In the same year the first European wire bridge was constructed in Scotland and it remained until 1839. This technique suffered a great development in Europe, which commanded the studies and constructions on this domain. The most relevant name linked to the investigation of this type of structures is Marc Seguin. This French Engineer constructed an experimental suspension wire bridge and studied its behaviour and construction process, as suggested in Fig. 1.



(a) (b)

Figure 1 : (a) Experimental bridge designed by Seguin; (b) Constructive process of a wire bridge (Wagner 1993) as related by (Dufour 1824).

Constructed in 1822, the experimental bridge of Seguin was 18m long and 0,5m wide (Wagner 1993). The constructive process of these structures begins with the positioning of the main cables; afterwards the deck is suspended to the cables using vertical wires distributed along the deck length.

The Seguin brothers were responsible for the construction of a large number of bridges all over Europe but, specially in France, country which led the construction of this kind of structures during the first half of the XIXth century, whereas the second half was dominated by the USA, specially because of the railway expansion and the emigration of European engineers to the West.

2 WIRE BRIDGES IN PORTUGAL

The first step to rehabilitate a historical construction is to know that it exists and that it is important to maintain it. Although there isn't much information about the construction of wire bridges in Portugal, it was possible to identify nine structures of this kind. The authors were informed on the existence of two other bridges located at Vinhais and Vila Real municipals.

The 9 bridges referred to above are listed in Table 1.

Table 1 : Wire Bridges at Portugal.

Name	Location 1 Village/municipal	Location 2 Village/municipal
Pensil	Porto	Gaia
Arame	Arnóia/Celorico de Basto	Rebordelo/Amarante
S. Aleixo de Além Tâmega	S. A. Além Tâmega/Ribeira de Pena	Salvador/Rib. de Pena
Veral	Beça/Boticas	Monteiros/V. P. de Aguiar
Gardunho	Santa Marinha/Ribeira de Pena	Dornelas/Boticas
Pedraça	Pedraça/Cab. de Basto	Pedraça/Cab. de Basto
Padroselos	S. A. Além Tâmega/Ribeira de Pena	Gondiães/Cab. de Basto
Adaúfa	Silgueiros /Viseu	Silgueiros/Viseu
Cabos	Ervedosa/Vinhais	Vale das Fontes/Vinhais

Only 4 of these structures are made of cables with wires grouped *in situ*, following the original process of construction of these structures. Unfortunately, the majority of them are in no conditions of being used and, in certain cases, are in a complete sate of ruin or were substituted by other structures. Probably some of them were constructed to respond to some needs that no longer exist and, thus, no maintenance procedures were applied to and the normal degradation process led them to the actual state of ruin.

Four of the structures referred to in Table 1 already disappeared or are in a complete state of ruin (bridges: Pensil, Pedraça, Padroselos e Adaúfa). In the case of the Arame bridge, it doesn't present safety conditions that allow it being used. Fig. 2 shows the actual aspect of the Padroselos bridge.

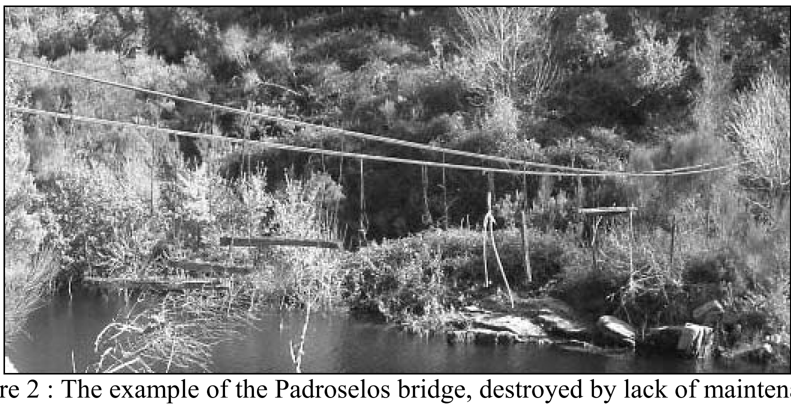
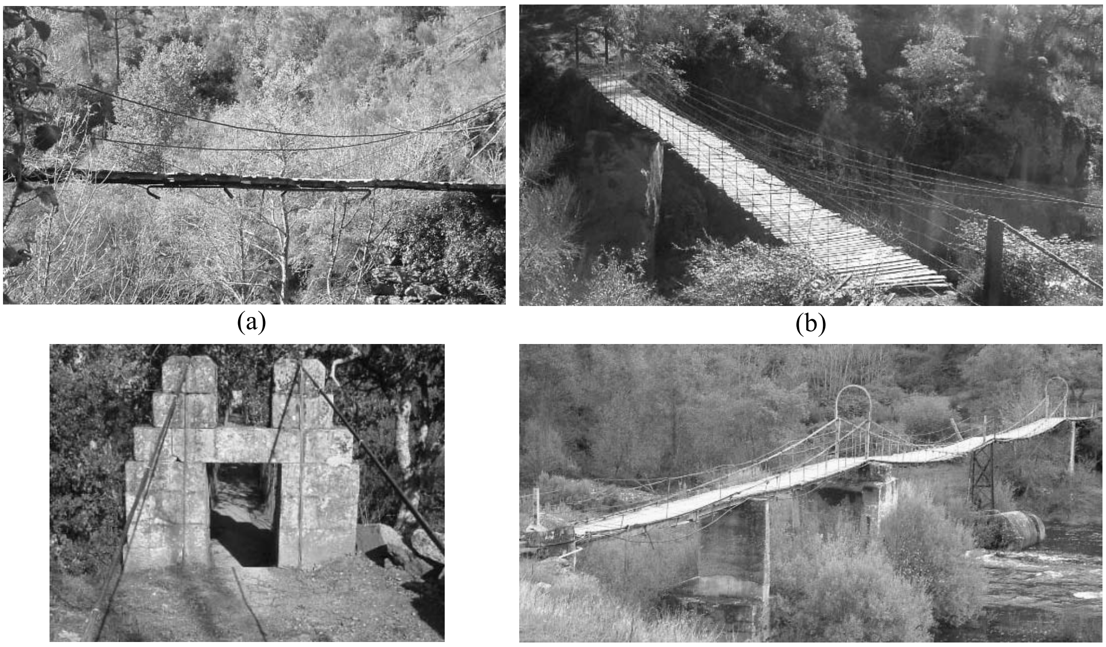


Figure 2 : The example of the Padroselos bridge, destroyed by lack of maintenance.

According to a brief study performed on a large number of structures of this type all around the world, the main causes for the wire bridges destruction are: Dismantlement, Substitution, Natural Causes, Collapse and Human Causes, respectively (Denenberg 2005). In Portugal the first cause is linked to the inexistence of proper maintenance procedures, which cause, especially on the wooden structure of the deck, serious damage. This aspect is frequently associated to a wrong selection of materials which often don't take into account the wood natural durability. In the case of the Adaúfa bridge, it collapsed under a flood.

Fortunately not all the Portuguese wire bridges have been abandoned. In a visit done in 2005, there were found 4 structures still being used: Gardunho, Veral, Santo Aleixo and Cabos, which are all presented in Fig. 3.



(a) (b) (c) (d)

Figure 3 : (a) Gardunho bridge; (b) Veral bridge; (c) Santo Aleixo bridge; (d) Cabos bridge.

All these structures have a wooden deck. The longest one is the Cabos bridge (about 70m long) and the shortest one is the Gardunho bridge, 22m long. The width of these bridges is approximately the same, about 1,5m, exception made for the Gardunho bridge which is 2,5m wide.

The Veral bridge went through a fire in August of 2005, which completely destroyed the deck.

The Santo Aleixo bridge is an emblematic case of success at the Portuguese scene, mainly because it is an *ex-libries* of “Ribeira de Pena” municipal. Fortunately also the Association of Municipals of Baixo Tâmega is determined to rehabilitate the Arame bridge and asked NCREP to study the best retrofitting technique. In the next point some considerations are done concerning these aspects.

3 THE ARAME BRIDGE:

3.1 Description

The Arame bridge links Rebordelo (municipal of Amarante) to Arnóia (municipal of Celorico de Basto).

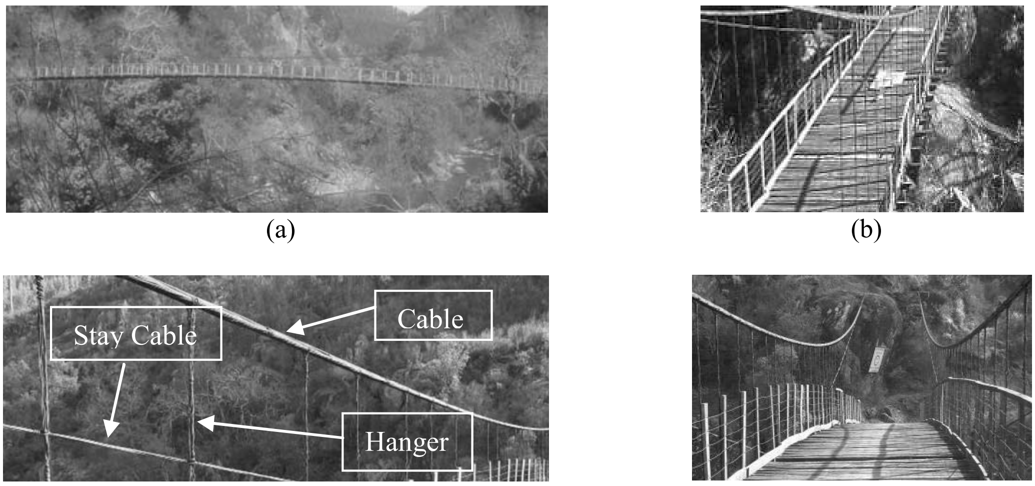
The “Ponte de Arame”, Arame bridge, has reactivated a previous link that existed in the same location but that was destroyed by citizens of Celorico de Basto with the intention to keep away a group of citizens from Vila Real (a near municipal). The bridge was built in 1926 and, as it was found in a local press article that there was no knowledge of any accident involving the structure in spite of the large vibrations caused by crossing the bridge. As the same article refers, the structure was used by small farmers to cross the Tâmega river with their animals, by motor-cyclists and by Rebordelo citizens to go to the Celorico market.

Nowadays, due the deactivation of the railway at Lourido (a small population near the bridge) the region became more isolated. Thus, the bridge retrofitting would create the necessary conditions to make easier the contact between the populations of the two river banks. Additionally the Arame bridge may become a tourist attraction element as it happens with the Santo Aleixo bridge.

The Arame bridge is 55m long and 2,5m wide; it is sustained by two cables, each one composed by three strand ropes. A cable has, approximately, 220 individual 3mm diameter wires, Fig. 4. The cables are linked to the deck by 104 vertical ties made of 8 individual wires (Costa et al. 2005a).

Each strand rope is protected by a dark coat which was identified by microscopically analysis. To improve the structural behaviour there are two stay cables that split from the main cables and go right through to the middle of the deck, where they pass under four central beams. These cables, one at each side of the bridge, allow reducing the vertical deformation of the deck. By direct observation, the authors concluded that the cables are directly anchored on the mountain rock.

Notice that the deck main components are the beams, placed transversely to the bridge longitudinal direction. These beams support the wooden longitudinal elements which support the wooden pavement. All the elements of the deck, the bridge pedestrian side protections included, are made of wood (Eucalyptus).



(a) (b) (c) (d)

Figure 4 : (a) Elevation view; (b) Perspective view; (c) Components identification view; (d) Internal view.

Due to the high level of degradation of its components, today the crossing of the bridge is interdict. This decision is based on the fact that the bridge doesn't fulfil the minimum safety conditions for its normal functioning.

3.2 Causes of interdiction

The *in-situ* analysis of the cables anchorages didn't show any rupture or signs that it could occur in a short time period. However, only a load test could correctly evaluate its strength capacity.

Four main damages were identified (Costa et al. 2005a):

- Damage A – Lack of wooden elements;
- Damage B – Wooden elements degradation;
- Damage C – Wires corrosion;
- Damage D – Biological attack.

The most relevant damage which was, certainly, responsible for the interdiction of the structure is damage A, which occurs not only on the deck elements but also on the lateral structure made for the protection of pedestrians. This damage is related to natural causes, material degradation, but also to human direct causes. There were also some wooden elements which manifestly wouldn't be able to respond to the bridge demands (damage B).

As for damage C, the wire corrosion which was responsible for a reduction of about 20% of the effective section was estimated using a microscope.

The biological attack, damage D observed near the cables anchorages is a major factor of degradation of these anchorages and, therefore, an indirect cause of collapse.

For all the 4 damages, a careful maintenance program could have been the key of its prevention i.e., of its no manifestation.

Table 2 summarizes the causes and some repair and prevention solutions of the identified damages.

Table 2 : Causes, repairs and preventions of the identified damages.

Damage	Causes	Repair	Prevention
A	Natural degradation; Human intervention.	Re-positioning of the missing elements.	Periodical maintenance
B	No preservation coating; Biological agents; Ambient agents.	Putrid wooden removal; Replacement of elements.	
C	Degradation of the coating; Ambient agents.	Rust removal; New coating protection.	
D	Surface conditions; Ambient agents.	Cleaning.	

3.3 Laboratorial and "in situ" tests

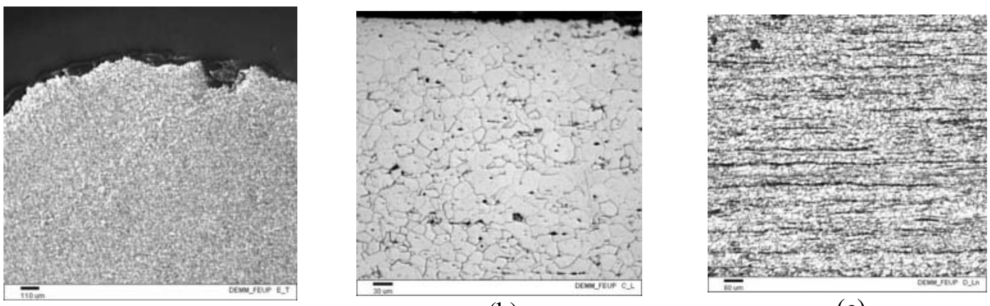
The material characterization is essential for a successful rehabilitation procedure because it allows choosing the best retrofitting method. In this way, several laboratorial analyses were made, namely (Costa et al. 2005b):

- Uniaxial tensile tests (wire) – it allowed determining the limit tensile stress of the wires, (f_{sk}=309MPa), the Young Modulus (E=171GPa) and other mechanical properties. The fracture surfaces were preserved to be used in the microscope observations;
- Electronic microscopy (EM) – the observations at the electronic microscope showed the ferritic microstructure of the wires (Seabra 1985). This steel typically has high ductility and tenacity;

  Although it wasn't possible to determine its intensity, it was possible to identify important corrosion phenomena.

  A large number of inclusions were observed, denoting a small purity degree of the material. These inclusions weren't found in the same quantities in all samples, giving an idea about the quality control of the production process.

  Fig. 5 presents a corroded wire section (5a)), a transversal section (5b)) and a longitudinal section containing several inclusions (5c)).



(a) (b) (c)

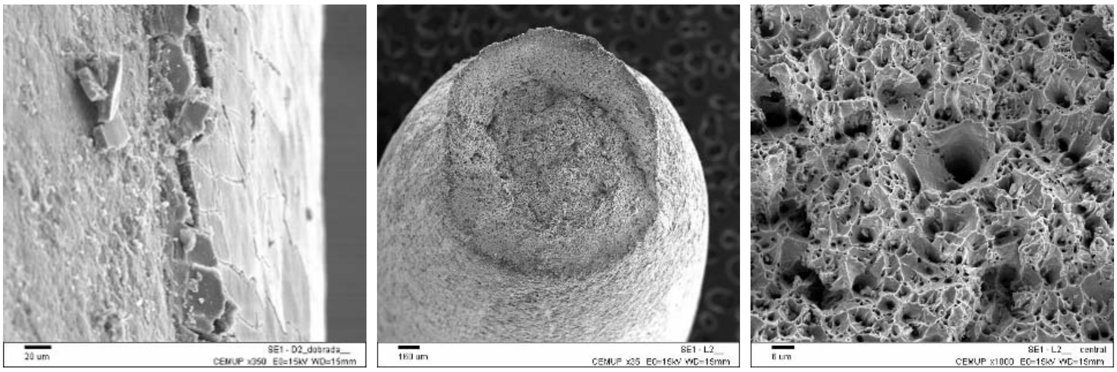
Figure 5 : (a) Corroded section; (b) Transversal section; (c) Longitudinal section.

- Scanning electronic microscopy (SEM) – the observations allowed determining the amount of corroded section. An average value of about 20% of corroded section was observed and it was used in the numerical analyses.

  Two different coatings were identified: an external polymeric one, about 9μm thick, suggested by a large amount of carbon observed on the spectrum, and an internal zinc coating. These protections, especially the external one, were cracked. In spite of this, the wires were considered to be relatively well preserved.

Although the uniaxial tensile tests gave, in almost all the cases, a very small ultimate extension, most probably because plastification had already occured on the wires in previous events (Branco 1985), the observation of the fracture surfaces confirmed the ductility of the material. This confirmation comes from the observed local area reduction and from the micron spherical sockets of the fracture surface (Callister Jr. 2002).

Fig. 6 presents the detachment of the external coating (6a)), a fracture surface (6b)), which is presented more in detail in the Fig. 6c).



(a) (b) (c)

Figure 6 : (a) Coating detachment (350x); (b) fracture surface (35x); (c) Detail of the fracture surface – micron spherical sockets (1000x).

- Volumetric mass (wood) – the inspections made at the structure showed the high degradation of the wooden elements. The main problem of these elements was the putridity caused by biological agents (fungus), reducing their effective section. However, even if the preservation of the deck had been proper done, the section of the wooden elements wasn't enough to resist the design loads.

  Moreover, the patrimonial value of this structure stays on its concept and not on the wooden structure materials, since the existing elements not only are made of a poor quality wood, has they recently substituted the older elements.

  For these reasons it was proposed to substitute all the wooden elements. Thus, it didn't make sense an intensive characterization of the material but just the necessary to estimate its stiffness and mass. In this way it was just determined the volumetric mass, which was lower than the expected (Coutinho 1999) due its degradation. Although there was a sample with a volumetric mass of 860kg/m^3 the average value was 670kg/m^3. This analysis also allowed identifying the wood specimen.
- Dynamic analysis – the main frequencies of vibration of the bridge were measured using seismographs. Due to technical problems, the modal identification couldn't have been done. Frequencies greater than 0.8Hz were found.

3.4 Retrofitting and Reinforcement

After concluding the previous phase the bridge safety conditions were analysed using the structural numerical software *Robot Millenium*. This analysis allowed verifying that the bridge had no capacity to respond to the nowadays design loads criteria, either in terms of the cables or the deck. Because of this incapacity, the bridge rehabilitation solution foreseen the strengthening of the wire structure with the positioning of new high strength cables. Although the old cables will not be removed and will be preserved as a heritage mark of the old structure, the solution disregarded the capacity of these cables. The new cables will be anchored at reinforced concrete blocks which will be anchored at the mountain rock through pre-stressing anchorages.

Due to the high degradation level of the pavement, as it was already referred to, it will be completely substituted using a higher resistant wood, the IPE. That measure took into account factors like the heritage and economical value of the wood. In fact the historical value of the bridge isn't on its materials but on its original conception which the rehabilitation strategy didn't intend to modify. Thus, the high flexibility of the bridge will be maintained but without compromising the pedestrian security because this is the main characteristic of this structure, giving authenticity to the retrofitted bridge. However, the dynamic behaviour of the bridge concerning transversal movements was improved with the inclusion of horizontal ties to increase the frequency values of the transversal vibration modes, decreasing significantly the occurrence of this type of vibration. This aspect was taken into account using four horizontal stay cables placed under the deck to increase the transversal stiffness.

Fig. 7 shows a cross section (7a)), the reinforced concrete blocks (7b)), the dynamic system under the deck (7c)) and an aerial view (7d)) (Costa 2005-c).

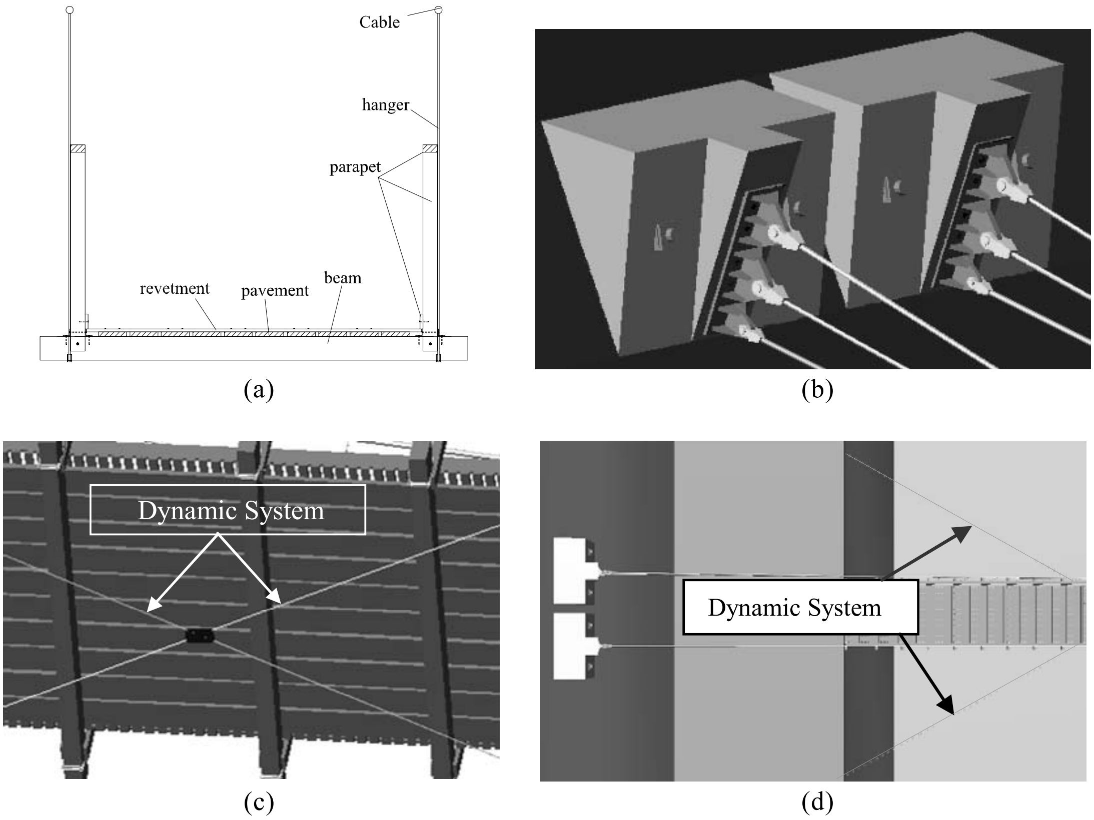


Figure 7 : (a) Transversal section; (b) Reinforced concrete blocks; (c) Dynamic system (3D view under the deck); (d) 3-D Aerial view.

4 CONCLUSIONS

This paper summarizes a study on wire bridges referring to aspects of its history and evolution. It also presents an inventory of this type of bridges existing in Portugal. In particular, it describes the rehabilitation methodology followed on a wire bridge that links two small villages of the North of Portugal.

The rehabilitation can't be done at any cost. It must take into account not only technical aspects but also historic, social and economic factors. It must take into account all this different perspectives so that the best solution could be adopted.

This work also shows the importance of the structural evaluation, since it dictates the guide lines for the intervention process. In the example presented in this paper, the structural evaluation was done through laboratorial and in-situ tests, and using microscopic technology.

The bridge safety conditions were analysed using a structural numerical software. The results confirmed the incapacity of the bridge to sustain the design loads and enforced the study of a strengthening procedure using high strength cables and a new deck using a higher resistance wood, the IPE. The transversal dynamic behaviour was improved with the inclusion of horizontal ties to increase the frequencies of the transversal vibration modes.

As a final global objective, this work aims contributing to increase the value and significance of built heritage, highlighting the importance of a good knowledge of the materials and their preservation conditions, and of its structural behaviour, to support a sustainable intervention.

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