Introduction
The Figueira da Foz Bridge over the River Mondego (Fig. 1) has a total length of 1421 m, including a 405 m long cable-stayed bridge and two approach viaducts with a length of 630 m on the left bank and 315 m on the right bank. The bridge was designed by Prof. Edgar Cardoso and built in 1982. The bridge is undergoing general rehabilitation and strengthening.

Description of the Structure
The cable-stayed bridge has a main span of 225 m and side spans of 90 m (Fig. 2). The pylons, 85 m above the water level, include four hollow concrete inclined legs. The stays, spaced 30 m along the deck, are made of galvanised wires passing over saddles at the top of the pylons. The bridge deck is a steel construction with two main girders, where the cable-stays are anchored, each one made of two 2 m-high I-beams interconnected by transverse beams spaced at 10 m. These transverse beams support longitudinal stringers spaced at 8.20 m which in turn support a reinforced concrete slab with a variable thickness of 0.13 m to 0.20 m (Fig. 3).

The deck of the approach viaducts have a concrete slab 0.18 m to 0.22 m deep supported by four longitudinal girders, spaced 5.20 m apart with a span of 45 m. The prestressed concrete girders have a rectangular section 0.40 m by 2.00 m at mid-span and 0.60 m by 2.50 m at the supports. The slab is prestressed in the transverse direction (Fig. 4). The deck is continuous for each viaduct. The girders are fixed to the transverse beams of the columns by dowels and pinned plumb bearings.

Rehabilitation Work
A detailed inspection and assessment of the safety of the structures according to the new codes showed that the bridge and the viaduct had suffered significant deterioration and that seismic strengthening was also required. The rehabilitation of such a construction requires proper planning and the introduction of working platforms (Fig. 5) which represent a significant cost of the works.

Cable-Stayed Bridge
For the cable-stayed bridge the main modifications were the following:
- Strengthening of the transverse top beam of the towers for seismic action by adding an external prestressing system.
Replacing and strengthening the anchorage system of the deck to the transition piers by transferring the tension forces with prestressing bars. General rehabilitation of the structure, including the saddles, the repairing and addition of a new corrosion protection coating of the steel elements as well as the local repairing and concrete surface protection of the pylons (Fig. 6).

Approach Viaducts

For the approach viaducts the main modifications were the strengthening of the main girders, the introduction of earthquake damping devices between the deck and the abutments, and general rehabilitation of the concrete structures, including local repairing and a concrete surface protection.

Strengthening of the main girders was made by external prestressing (Fig. 7). This work was deemed necessary due to the fact that the live load adopted in the design was lower than the current code values as well as the damages observed in the beams (cracking, concrete defects). The prestressing system included 4 cables for each beam, with a total of 16 strands for each internal beam and 14 strands for each external beam. A trapezoidal layout was adopted with deviators under the two existing transverse beams in each span. The strands are placed inside a Ø 75 mm High Density Polyethylene duct and injected with cement grout. A double High Density Polyethylene duct was used at the deviators. Near the active anchorage a free unbounded length was provided to enable future cable replacement. Along that length the strands are protected by individual ducts and grease. At the deviators and at the anchorages the High Density Polyethylene duct is inserted into a Ø 88,90 mm steel pipe.

The deviators include a curved plate segment from a Ø 101,60 mm steel pipe connected to a steel box fixed to the main girders and filled with grout to provide a rigid support to the cable (Fig. 8a). A prototype test was made to check the behaviour of the deviators and the cables.

The anchorages are standard active anchorages with galvanised steel covers. The anchorages are fixed to anchor concrete blocks which are fixed to the transverse beams and deck (Fig. 8b).

The cables were stressed to 65% of their ultimate strength to achieve the effective prestressing force of 2480 kN for the internal beams and 2170 kN for the external beams.

New energy dissipating devices were introduced and provided between the deck and the abutments. The dowel bars used to fix the deck to the abutments were found not to be robust enough and the connection to the beams did not guarantee the required strength. A three dimensional model also showed that the shorter column bents did not have the required strength. To install the viscous dampers (one in each of the four beams) the abutment had to be modified to accommodate the dampers and new sliding bearings between the girders and the abutment (Fig. 9).

To establish the characteristics of the viscous dampers, a three-dimensional non-linear time-dependent dynamic analysis was performed with 10 artificial accelograms to simulate the Eurocode 8 design earthquake action in Portugal. The viscous dampers, one for each beam, were defined by the constitutive law \( F = c \cdot V \cdot a \). A parametric study was performed with \( c = 500; 1000; 1500 \text{ kN} \cdot \text{s/m} \cdot \text{a} \) and \( \text{a} = 0,1; 0,2 \).

For the left bank viaduct the selected dampers have a constitutive law \( F = 1000 \cdot V \cdot a \). The efficiency of this solution was the following:

- The earthquake design longitudinal displacement was reduced from 79,90 mm (obtained in a model with a free longitudinal displacement at the abutment) to 32,00 mm at the abutment and from 88,60 mm to 39,50 mm at the transition pier.
Fig. 9: Details of the abutment changes to install the dampers

The force transferred to the abutment was reduced from a total value of 11,268 kN (obtained in a model with a rigid connection of the deck to the abutment) to $4 \times 802 = 3208$ kN.

Yielding at the shorter columns for the design earthquake is avoided with the introduction of dampers.

The dynamic behaviour model was checked with the experimental evaluation of the vibration modes and frequencies on site.

Conclusions

Although the structure presented considerable deterioration, the inspections of the stays of the cable-stayed bridge showed that the galvanised wires and the anchorages were in good condition. That information was a major contribution to the decision of maintaining the stay cable system.

The design concept of modifying the viaducts – installing external prestressing and dampers – is straightforward but the execution required very careful and detailed preparation of the structure due to the complex geometry of the bridge.

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SEI Data Block

**Owner:** Estradas de Portugal E.P.E., Almada, Portugal

**Rehabilitation Design:** Proponte, Lda, Lisbon, Portugal

**Contractor:** Soares da Costa, SA, Portugal

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**Prestressing steel (ton):** 762
**Surface protection:** 22,500
**Steel structure (m²):** 93,500
**Concrete (m²):** 11,300
**Concrete Repair (m²):** Total cost (EUR million): 9
**Service date after rehabilitation:** June 2005

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