IABSE British Group Henderson Colloquium.
Magdalene College, Cambridge. 5-7 July 2004.

Designing a Suspension Bridge for the Consequences of Hazards - Case Study: Metsovitikos Bridge

Andrew Martin (Arup)

Introduction

In 1998 Arup, supported by Wilkinson Eyre Architects, won an international competition for the design of a bridge to carry the proposed Egnatia Odos motorway across the valley of the Metsovitikos River, high in the Pindos Mountains of north-west Greece. The winning design was for a suspension bridge with a 550m long deck passing over the 145m deep vee-shaped river valley. The structural form of the bridge was innovative in a number of ways most notably in that there were no towers, the main suspension cables being anchored directly into the sides of the valley. Also, the main cables and hangers were set in an inclined plane to enhance the architectural qualities of the bridge. The general arrangement of the bridge and the deck cross section are shown in Figures 1, 2 & 3.

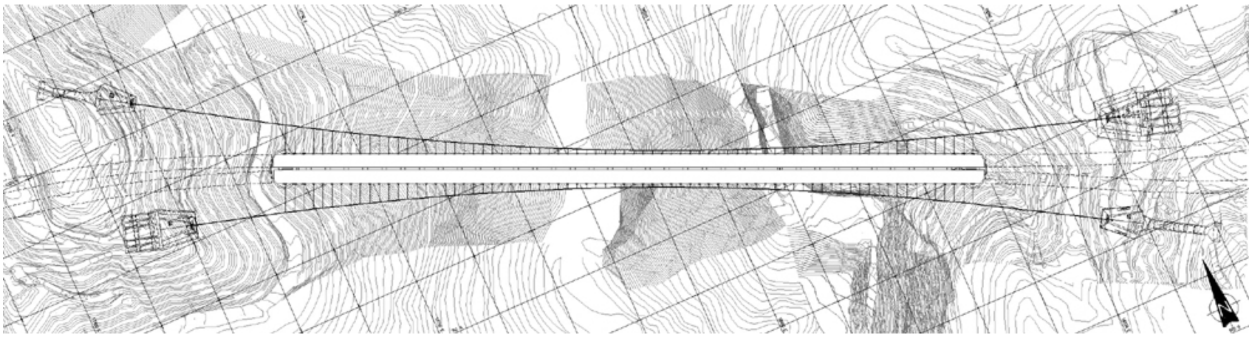


Figure 1. Plan on bridge.

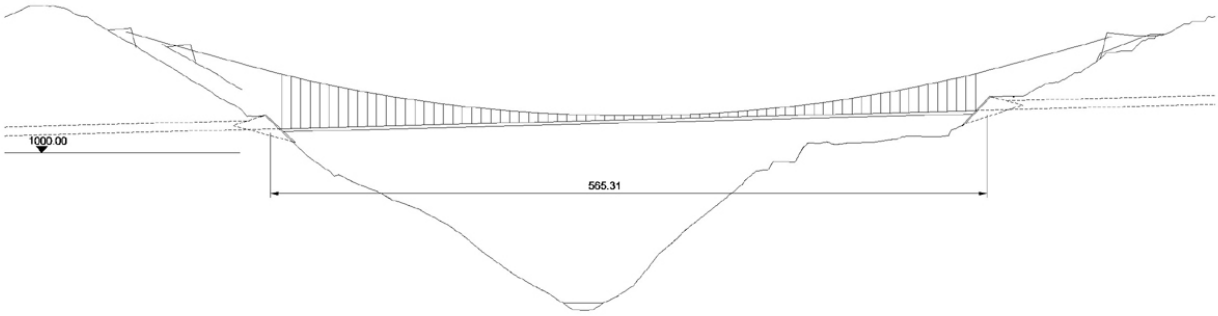
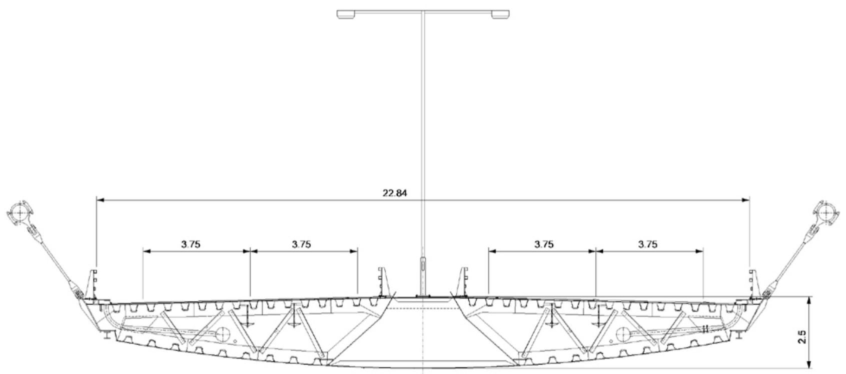


Figure 2. South-west elevation.

Figure 3. Deck cross-section (dimensions in m).



Bridge engineering requires consideration of the structural consequences of hazards. These may either be naturally occurring environmental hazards, such as earthquakes, winds, and storms, or actions due to interventions by man, such as vehicle or ship collisions. Various methods and design rules have been developed by which the effects of hazards on a bridge can be characterised, analysed and accounted for in design and these provide a sound basis for the design of the majority of bridges. However, structures such as Metsovitikos Bridge frequently require consideration beyond the scope of published guidance. Also, developments in engineering practice and the increased expectations of clients sometimes require previously unconsidered hazards to be taken into account.

This case study does not set out to provide a comprehensive guide to the design of suspension bridges for the consequences of hazards, but instead will illustrate how particular issues relating to the effects of specific hazards were dealt with in the design of this unconventional bridge.

Design Basis

A large and complex international project such as Metsovitikos Bridge required a clear and unified philosophy for structural design which would be acceptable to all of the parties involved. Although still at prestandard stage, the structural Eurocodes were chosen as the framework around which the Design Basis for the bridge was developed. The Eurocodes were considered to offer particular benefits compared with more established standards, particularly in terms of their:

- Broad technical acceptance across Europe;
- Specific consideration of accidental loading cases;
- Consideration of seismic effects.
- Codified requirements for the design of high-strength cables in bridge structures;

Even so, the structural form of Metsovitikos Bridge placed it beyond the scope of the Eurocodes in some respects and in these cases state-of-the-art knowledge was used to develop a sound basis for design.

Structural Behaviour of the Bridge System

At an early stage it became apparent that the innovative structural form of Metsovitikos Bridge gave rise to effects that would not be experienced in a conventional suspension bridge. Of particular importance was an effect caused by the 'oversail' of the cables past the end of the bridge deck.

In a conventional suspension bridge the relative movements of the main cables above the ends of the bridge deck (i.e. next to the towers) under vertical imposed load are relatively small. However, for Metsovitikos Bridge the large horizontal distance between the ends of the deck and the cable saddles caused significant vertical displacement of the cables above the ends of the bridge deck. The bridge deck is supported vertically at the abutments and consequentially the end hangers supporting the deck go slack and the deck has to span to the first hanger remaining in tension, as shown in Figure 4.

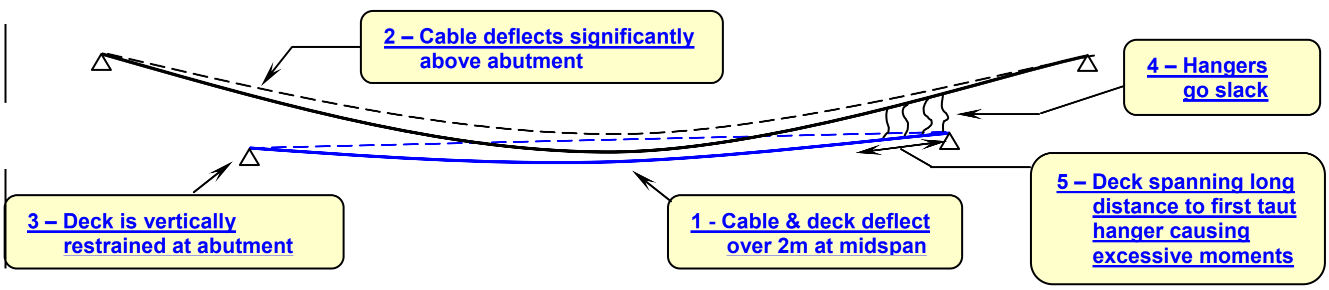


Figure 4. Structural effects of main cable 'oversail' (uncorrected).

This unwanted behaviour was overcome by introducing prestress into the end hangers of the suspension system and by tying the ends of the deck to the ground, producing the effect of a 'virtual saddle' on the main cable by fixing its position in space above the ends of the bridge deck. Under increasing imposed load the tensions in the end hangers were effectively allowed to decrease, but never to a degree which might allow them to go slack.

Whilst being of general interest, this behaviour and the measures adopted to counter it had knock-on effects in the solution of issues concerning extreme and accidental actions.

Seismic Effects

The location of the bridge in the Pindos Mountains is one of significant seismic activity. The form of the bridge and its importance on the Egnatia Odos motorway placed it beyond the scope of the codified measures for earthquake design in both Eurocode 8 and the Greek seismic design code E39/93. Instead a bespoke Performance Based Seismic Engineering approach was developed, with reference to the internationally recognised standard ATC-32. This took into consideration:

- Horizontal and vertical ground movements;
- Spatial variability of the ground;
- Possible non-linear soil behaviour (site response);
- Non-linear structural behaviour (material and geometric);
- Two-level limit state design.

For the long period motions expected for the bridge, site-specific design spectra were developed by Probabilistic Seismic Hazard Assessment (PSHA). The PSHA defined two evaluation events for the design of the bridge, together with acceptable damage levels for each, which are summarised in Table 1.

Design Ground Motions			Seismic Performance Criteria (from ATC-32)		
Evaluation Level	Chance of Exceedance in 120 years	Return Period (years)	Service Level (1)	Damage Level (2)	Ductility Level (3)
Functional	40%	235	Immediate	Minimal	Elastic
Safety	10%	1139	Immediate	Repairable	Elastic

Notes
(1) Service Level. Immediate – Full use by normal traffic almost immediately after earthquake.
(2) Damage Level. Minimal – Essentially elastic performance
Repairable – Repairable damage without loss of functionality.
(3) As the bridge had limited capacity for ductile response, forces and displacements from seismic actions were limited to the elastic range.

Table 1. Summary of Performance Based Seismic Engineering Design Criteria

Having set the basis for the seismic performance, the effects of seismic actions on the bridge were added to the requirements for normal use as the criteria for the development of a suitable system of articulation for the deck. The significant design choice was made to allow the bridge deck to move in a controlled manner under seismic loads rather than to attempt to restrain the deck using fusible fixed bearings. The articulation arrangement at each end of the bridge deck is shown in Figure 5.

Double-pinned 'pendel' arms were provided to give vertical support to the ends of the bridge deck box girders and to carry the end hanger tie-down forces, whilst also allowing the deck to swing longitudinally under seismic loading. Under variations in ambient temperature the suspended bridge deck either hogged (cold) or sagged (hot) generating rotations at the ends of the deck which gave unacceptable discontinuities in the longitudinal highway profile. To overcome this the box girders were modified so that the trafficked stiffened steel deck was separated from the main stiff spine beam for a short distance into the span. These 'flexing panels' were supported on conventional bearings adjacent to the abutment and would bend independently of the main deck girders to give an acceptable highway profile under all design loading conditions. As a final measure the ends of the flexing panels were tied down to the abutments adjacent to the bearings to prevent uplift.

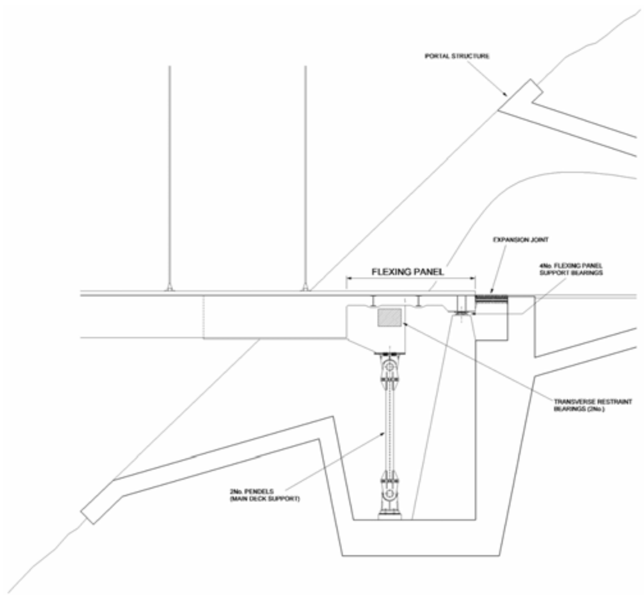


Figure 5. Articulation of deck end at abutment.

Accidental Damage to End Hangers

For cable-stayed bridges it is normal design practice to make allowance for the removal of a stay cable, either for maintenance replacement or because of accidental damage, whilst maintaining the full structural performance of the bridge. This approach is included in the Eurocodes and was applied to the hanger cables of Metsovitikos Bridge. Whilst relatively unremarkable on first consideration, this requirement had particular significance for the hangers at the ends of the bridge deck. As referred to above, the end hangers were an integral part of the structural system of the bridge as they were to be pretensioned during construction to provide the 'virtual saddles' to regulate the movement of the main cables.

To give the necessary pretension the end hangers were sized as 120mm diameter locked coil cables, compared with the 60mm diameter cables used for the hangers elsewhere. For aesthetic reasons, a feature of the bridge design was the positioning of the hangers at the comparatively close spacing of 7.5m along the bridge deck. As the Eurocode requires cables within a projected area of 10m x 10m to be considered for simultaneous removal, both the second and third end hangers were also specified to be 120mm in diameter to provide for the circumstances of two of the three end hangers being removed.

Accidental Damage to Cable System by Fire

Provision is made in the Eurocode for consideration of the effects of fire on cables to be considered in design, if required by the appropriate authority. As with many issues in civil and structural engineering, once a new design criterion has been considered for a particular project then the door is opened for it to be taken into account on future projects. For the Arup-designed Oresund Bridge the effects of fire on the cable system had been considered. Therefore, although the Eurocode requirement was not mandatory, similar considerations of the effects of fire were made for Metsovitikos Bridge.

As a first step, the existence of a credible case for a fire which would affect the cable system was established. The position of the bridge on the Egnatia Odos motorway readily provided a *prima facie* case. Metsovitikos Bridge is approached from the west by a continuous climb of several tens of kilometres, much of which is in tunnel. Experience has shown that fires in long highway tunnels are most usually caused by overheating vehicles and the scenario of a less-than-well-maintained lorry catching fire at the bridge site after a long climb in low gear up the gradient of the Egnatia Odos did not seem totally implausible. Similarly, the likely reaction of the driver of such a burning vehicle to drive out of the tunnel to the relative safety of the bridge deck and then abandon the burning vehicle added to the case for fire to be considered as a valid design criterion.

Specialist advice was sought from fire engineers on the intensity of the fire to be considered which was set at 90MW burning for 90 minutes. The visible flame envelope for a vehicle fire on the bridge under a 5m/s crosswind is shown in Figure 6.

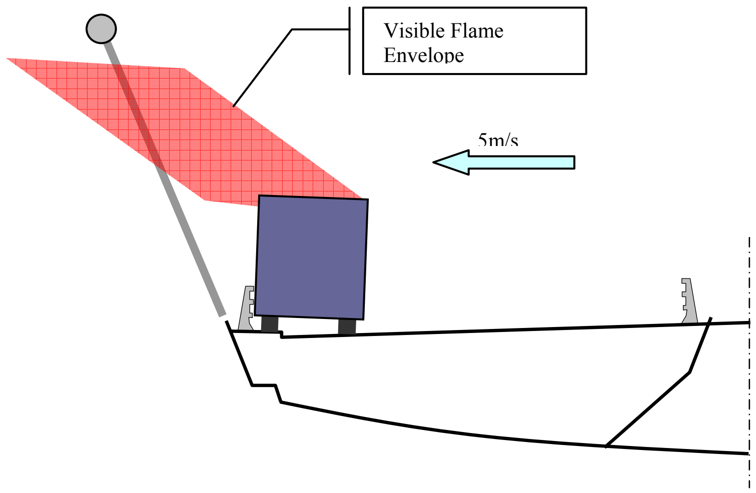


Figure 6. Visible flame envelope of design vehicle fire at 550 °C.

The principal effect of fire on steel is to reduce it yield stress. For normal structural steels much of the material strength is recovered on cooling. However, suspension bridge hangers and cables are constructed from high strength wires that gain their strength by cold working. When subjected to elevated temperatures an irreversible loss of strength take place. Whilst the loss of one or two hangers can be allowed for in design, with the fire-damaged components being replaced, similar effects in the wires of a main suspension cable would not be so easy to remedy. The effect of such loss of strength through fire could therefore have significant consequences on the future adequacy of the bridge. In trying to assess the magnitude of this risk, data was sought on the material properties of cold drawn wires at high temperatures and after cooling, but none was available either from wire manufacturers or in the literature. Anecdotal evidence suggested that a main cable of a large suspension bridge had once been exposed to a significant fire and that tests had been carried out to determine the degree of loss of strength of the cable wires, but also that the matter had remained a private and unpublished matter. Due to the sudden end of the project during detail design full consideration of this issue was never concluded, but will perhaps merit further consideration in the future.

Conclusion

The design of Metsovitikos Bridge was an exciting and challenging project in which consideration of the consequences of various hazards on a novel and innovative suspension bridge tested the skills of all those involved to a high level. Regrettably for the Arup-Wilkinson Eyre team the project client abandoned the scheme in 2001 so this imaginative bridge will not be built.