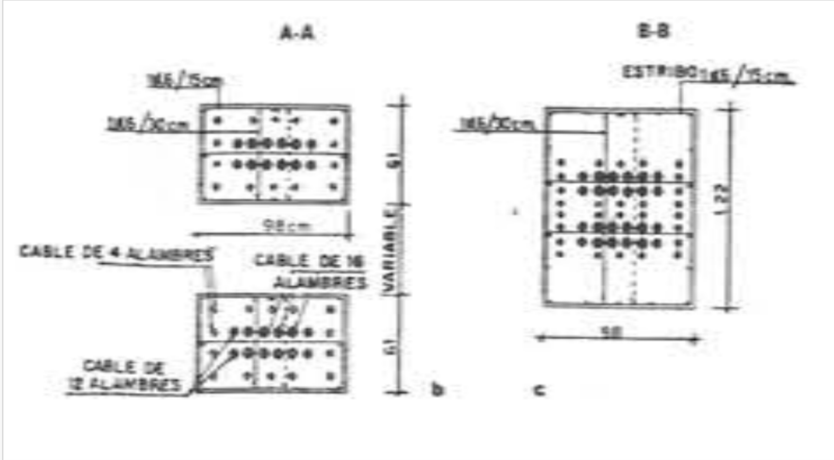
Understanding Morandi - Part 1 - The Prestressed Conrete Cable Stays

I'd like to explain a bit from what I understood so far about the (in)famous Morandi prestressed concrete cable stays. This is an evolving and frequently updated article (initial version 17.8.2018) I'd like to share for your interest, challenge and discussion.
Grateful for any comments (please scroll down to page footer).

Riccardo Morandi, the lead engineer of the Polcevera Viaduct, was one of the rare engineers to employ prestressed concrete cable stays in bridges. It made me curious to learn about the reasons, and to learn how the system functions. First look on Pylon 9:

Pylon 9: The cable stay consists of two distinct stays in their lower part which merge half way up towards the tower (Hasen 2015)

Let us consider two cross-sections of those cable stays:



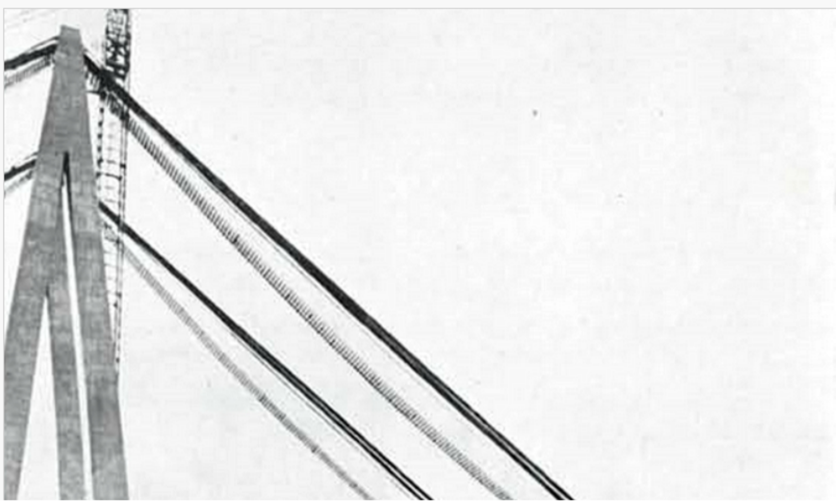
Two cable stay cross sections. 24 A-cables and 28 B-cables (Morandi 1968)

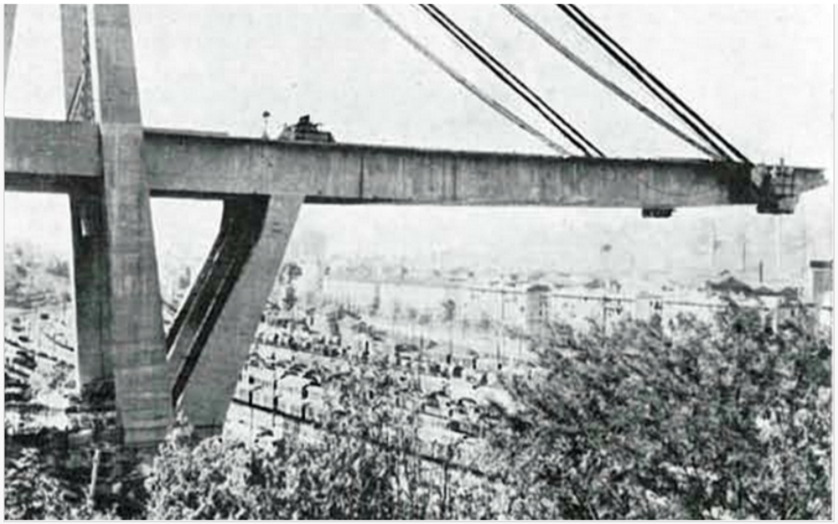
In the drawing above, the right cross-section is located somewhere in the upper part of the cable stay, towards the top of the pylon. The cross-section to the left is located in the lower part: In fact there are two superimposed cable stay packs that merge further up. Adding complexity to the static system, esp. in the long run.

Also notice the cross section drawings show cables of two different diameters: Thicker A-cables and thinner B-cables. Both have very different functions and assembly modes:

The stronger A cables were first lined and tightened, supporting weight of the box-type cantilever carriageway at their ends. So there was no concrete around them yet. Therefore, no precise Pre-stressing was possible at this point. This will be done in a next step with the B-cables, which I'll explain hereafter.

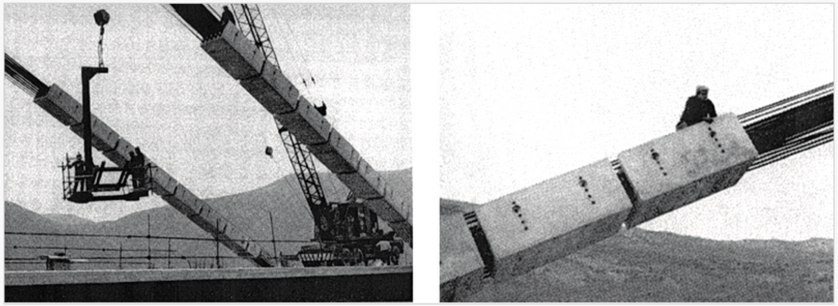
The photo below shows this construction phase: Two sets of 12 inner A-cables have been spanned, still without the concrete boxing around them, but already supporting the cantilever carriageway.





24 raw A-cables supporting part of the cantilever deck, prior to conrete casting (Morandi 1968).

In a further construction step precast concrete box elements have been appended along the the inner A-cables, filled with concrete and finally pre-stressed by 28 outer B-cables.



Precasted concrete box elements are being attached to the main A-cables of Capriano Viaduct around 1977 . The elements will later be filled with concrete and then prestressed with additional B-cables (Sala 2016).

It may be adequate to note that the outer B-cables were those that were mechanically prestressed to keep the concrete girder under compression. And therefore resulting in a prestressed beam.

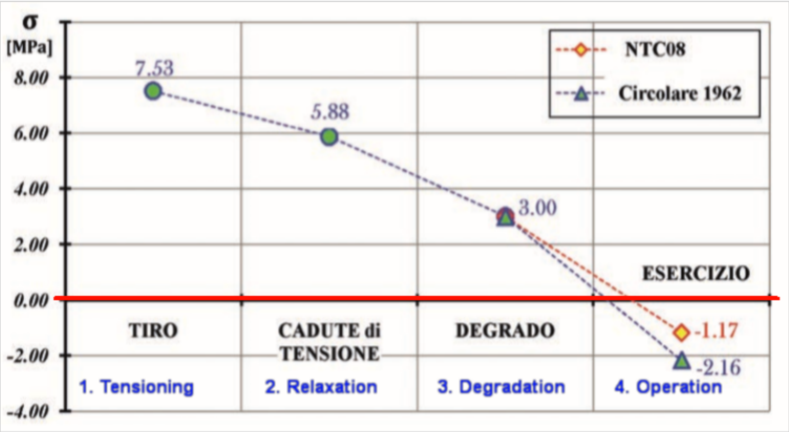
Morandi thought that loading major tension on the outer B cables and less tension on the inner A-cables would reduce mechanical wear and tear of the "main" A-cables. The tension applied to the outer B-cables should be only as tight as to just support the maximum bridge load (= road vehicles). Remember that only the tension of the outer B-cables could be precisely calibrated during construction phase.

However, a major problem arose: After the concrete box around the cables was constructed, the resulting sag and weight induced lengthening changed the already fixed effective (=straight) length. Therefore the carriageway was not (and would never be) horizontally well-levelled. In the later years it seemed they tried to level out the carriageway box girder by adjusting the "V" abutments (which I don't understand how this would have been possible).

In addition to this, a series of further challenges needed to be taken into account, some of them could have contributed to the recent bridge failure:

- Because the prestressed concrete beam is very thin in relation to its length, and also because of the noticeable sag of the (see side views of the bridge), the compression that could be applied to it was very limited. Morandi knew this very well: Applying too much compression through the B-cables would have resulted in non controllable destructive effects.

  So, and this is a bit astonishing, Morandi has chosen the B-cables to be tensioned for a low compression range from nearly zero compression (at fully loaded carriageway) to a rather low positive value (when empty carriageway).
- In other words: From the very beginning, the strays were not compressed as tight like conventional pres-stressed beams (i.e. of bridges). Their positive attributes therefore do not fully apply to Morandi's pres-stressed cable strays.
- Adding to this, during years of operation, highly tensioned cables are inevitably exposed to the phenomenon of relaxation, a loss of tension occurs. Therefore also compression in the concrete stray decreases over time until reaching a critical point, total relaxation.
- Unfortunately low/zero longitudinal compression in a thin beam makes it prone to cracks, rapid degenration and intrusion of water. It is likely pylon 11 reached this state before it was strenghtened.
- The similar Carpineto Viaduct, built 10 years after the Polcevera Viaduct, suffered the problem of total relaxation as well and was therefore thoroughly assessed and modelled (FEM) around 2013 by Della Sala et al.



Longitudinal compression in concrete prestressed stay beam of similar Carpineto Viaduct. After initial tensioning in 1977 pressure was set to 7.53MPa (77kg/cm²), which decreased more than half to around 3MPa until 2013. Under heavy load operation, the longitudinal compression would fall below zero, resulting in rapid degeneration and putting stability at risk (Sala 2016 - modified to include english translations)

- Because the steel cables are bonded to the surrounding concrete, small cracks in the concrete inevitably lead to corrosion and additional wear.
- Bacause the cables can not be inspected as they are immersed in concrete, corrosive effects and single wire strand failure can not be detected. Single wire cable fails are not a problem and may happen to all cables even aerial cablecars without causing imminent danger.
  In more modern designs, to enable constant monitoring, cables are electrically insulated so that single wire failures can be detected by changes of electric resistance of the cable.
- Neither can the current compression in the concrete be measured easily.
- So both low tension and high tension need to be avoided and a very wise range of

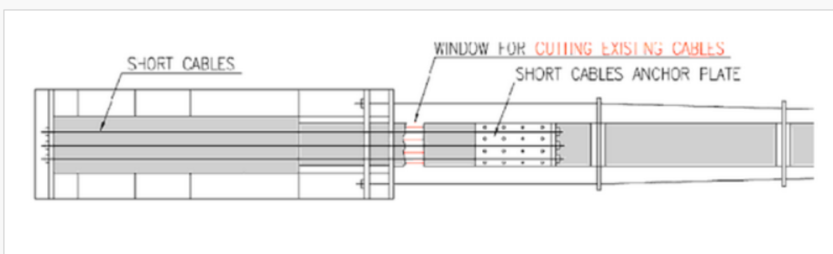
prestressing forces to be determined and applied during planning and construction, with possible re-calibrations later.

> Because of steel relaxation and concrete viscosity, cable tension needs to be monitored in adequate intervals and, if necessary, re-calibrated. Unfortunately, neither effective monitoring nor re-tensioning is possible in the Genova design. The lack of precise, thorough and continuous monitoring possibilities (corrosion, wire strand failures, concrete compression) is not a helpful feature and may lead to unobserved critical degeneration.

Around 1993 pylon 11 received twelve additional external reinforcements cables to mitigate some of the above issues:

Pylon 11: External reinforcement cables installed 1992-1994. (Hasen 2007)

Several challenges arose:
One major problem was that the tension applied to those additional cables should not increase the total combined compression of the thin concrete beam. Applying additional pressure would have been likely to damage the thin concrete beam structure. The successfully applied solution could be summarized as extremely complex: It consisted in cutting a section of the old concrete beam to also cut the old cables inside while subsequently applying more tension to the new external cables.



Pylon 11: Additional reinfocement cables anchoring, cutting of existing cables (Malverde 2010)

About this article:
I examined a number of articles about structural analysis and repair of Morandi type bridges, by different authors and Riccardo Morandi himself. It could be interesting to observe that most authors give rather different explanations why Morandi has chosen this particular design. This may be an evidence that there might not be a substantial rational argument in favor of this design when considering its draw-backs. Riccardo Morandi himself gives two main reasons (Morandi n.d.): To eliminate vertical movement of the cantilever bridge deck (and therefore reduction of torsion at its fixed end) and to lower stress on the inner A-cables, mostly due to attenuated effects of variable bridge load.

by Kristian Hasenjäger (Last updated: August 19, 2018)

Bibliography:

This article is an iteratively evolving work. The bibliography will be available once the article is finished.

Comment on this page...

3: Guest - 9 days ago Aug 21, 2018 8:13:18 AM

It seems to me that Morandi used that technique of concreted strays to save a lot of work for him. Bridge constructing in the manner of a prefab. Furthermore it appeared to me ignorant to construct it without any possiblity of maintainance. Means to me: I'm done, now it's your turn.

2: System Admin - 10 days ago Aug 19, 2018 10:19:03 AM

Dear Giulio,

thank you for your interesting observations

> Is it correct to understand that with the addition of external
> reinforcement cables all the internal one are cut and hence useless ?
The cables have definitely been cut. According to the above drawing however the old stay has statically been re-connected.

> Do you have a quality drawing where we can see the dimensions ?
To which dimensions are you referring to? The cable stay cross section seems to measure 98xm x 122cm in its merged upper part.

> Also, I am actually curious about the towers columns...
> from the pictures of the disaster there seem to be very little reinforcing there.
I share your observation about the apparently low steel reinforcing. However due to the uncommonly large dimensions of the cross-sections this may be a biased consideration.
I would add that I am surprised how the towers have crumbled down into so many pieces, like an ancient castle. Instead I would have expected the tower frames to at least partly resist the rupture of one cable stay. Or at least bigger monolithic structures.

1: Guest - 11 days ago Aug 18, 2018 4:12:50 PM

thanks for this information, would you be able to share the articles you mention ?
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