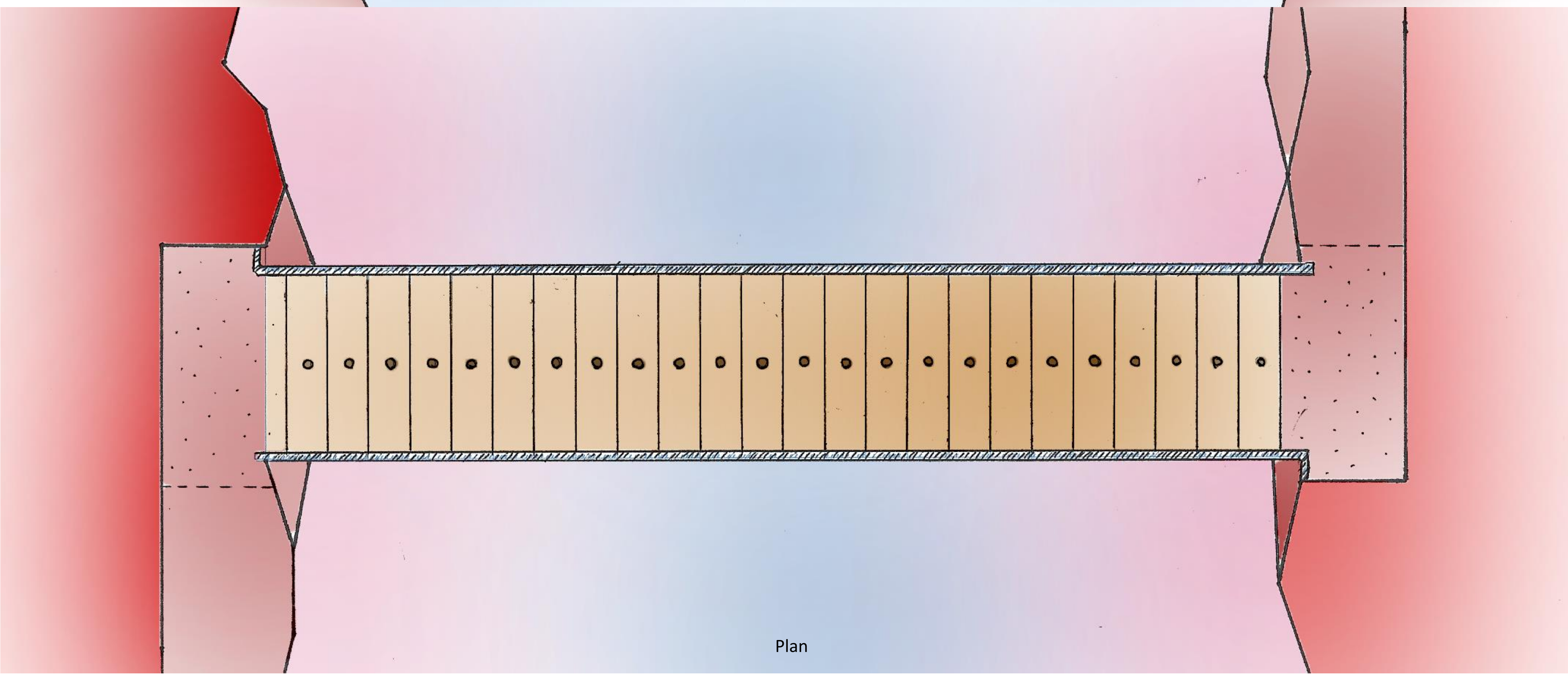


Structural system: A walk on arch bridge formed from UHPC blocks, a cable below, and stays connecting the two. The arch and cable have foundations in the cliff faces on each side of the bridge.
Key dimensions: Bridge length – 25m, Walking width – 4.1m, Balustrade height – 1.3m.

Design feasibility check: Reflecting the slim arch, the majority of internal forces are due to post-tensioning and live loads, rather than self-weight. The UHPC voussoirs, springers and foundations all work at around 50% of their expected capacity. Snap-through is the greatest concern to be mitigated, with an allowable spread or longitudinal shortening of ~30mm. However, the materials and technologies are available: factory produced UHPC with machined end details, surveyed foundations and detailed analysis are well within these tolerances. Suggested mitigations include compensation for any expected UHPC strain or shrinkage over time and movement of foundations, as well as monitoring of any foundation spread. Similarly, the slim arch requires precision in its manufacture and assembly to ensure no local buckling modes are critical. Here, assembly at the top of the canyon enables a greater level of precision than could be achieved at path level.

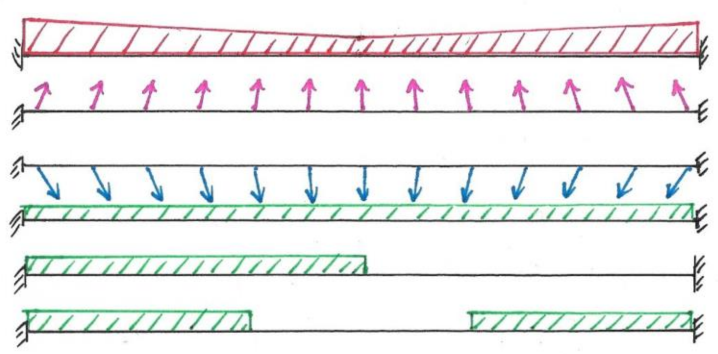
Reciprocal diagrams offer an immediate understanding of the interactions between the arch and the cable, allowing exploration of feasible geometry at concept stage. Approximations of key outputs can be found and checked simultaneously: forces in the springers and UHPC blocks, the bridge's ability to resist different load patterns, and maximum gradient. The reciprocal diagrams direct the thrust lines in the arch, dictate the underslung cable geometry, and indicate the forces in and between each element.

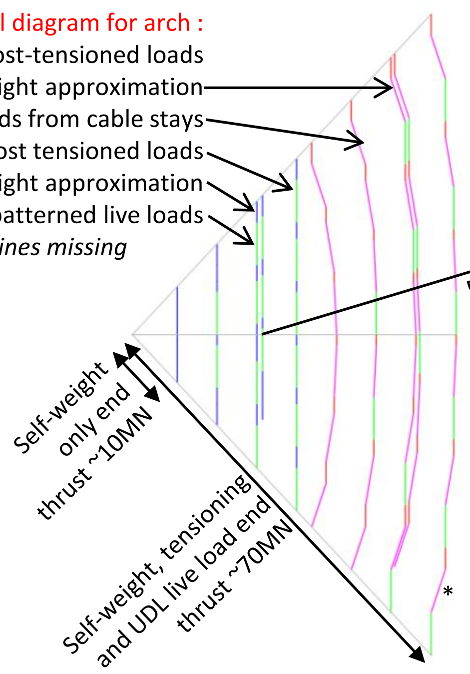
In summary, using an underslung cable allows a thinner arch profile than would otherwise be possible, allowing full use of UHPC's high strength, a reduction in weight and a dramatic elevation. The larger rise of the cable reflects the relative capacity of the cable and its rock anchors compared to the arch and its springers. A summary of our analysis is shown in the diagrams below:

1) Arch loading (below):
Self-weight approximation (top)
Lifting eye loads
Cable stay loads
UDL live loads
50-50 pattern loads
33-34-33 pattern loads (bottom)

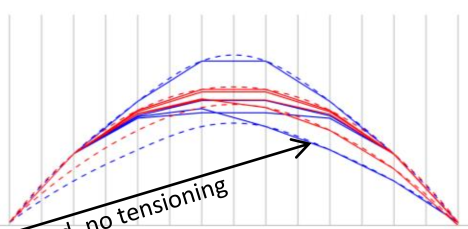
2) Reciprocal diagram for arch :
Outer curved lines: post-tensioned loads
Red: self-weight approximation
Pink: loads from cable stays
Inner straight lines: non-post tensioned loads
Blue: self-weight approximation
Green: live loads including patterned live loads

Note: this reciprocal diagram has some lines missing and is has been stretched to aid clarity.



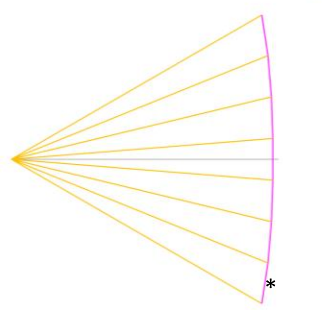


3) Thrust lines
Blue: no cable
Red: with cable
Dotted: envelope of thrust lines



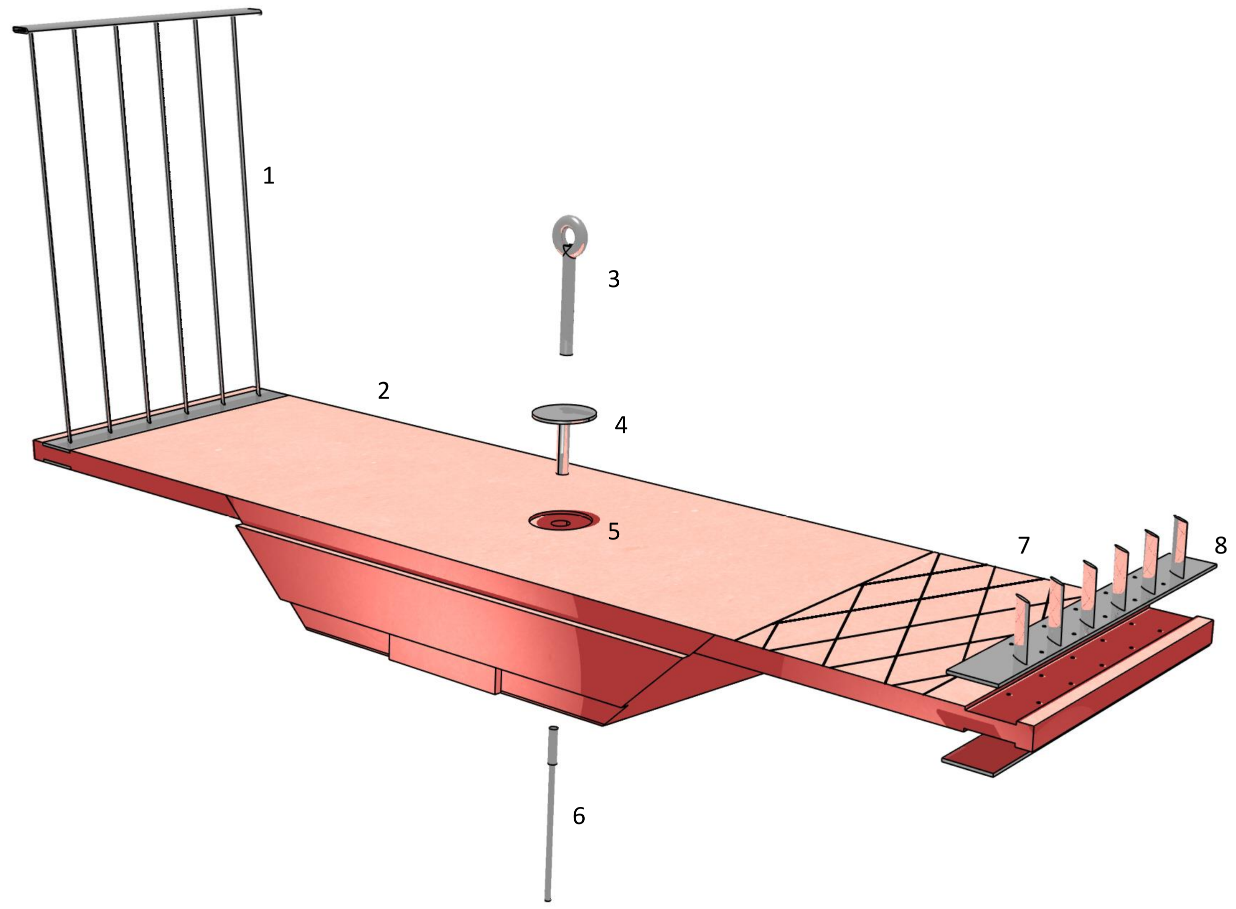
4) Geometry
Bridge geometry (black), stays (pink) and cable (gold)

5) Reciprocal diagram for cable of stays (pink) and cable loads (gold) to determine cable geometry.

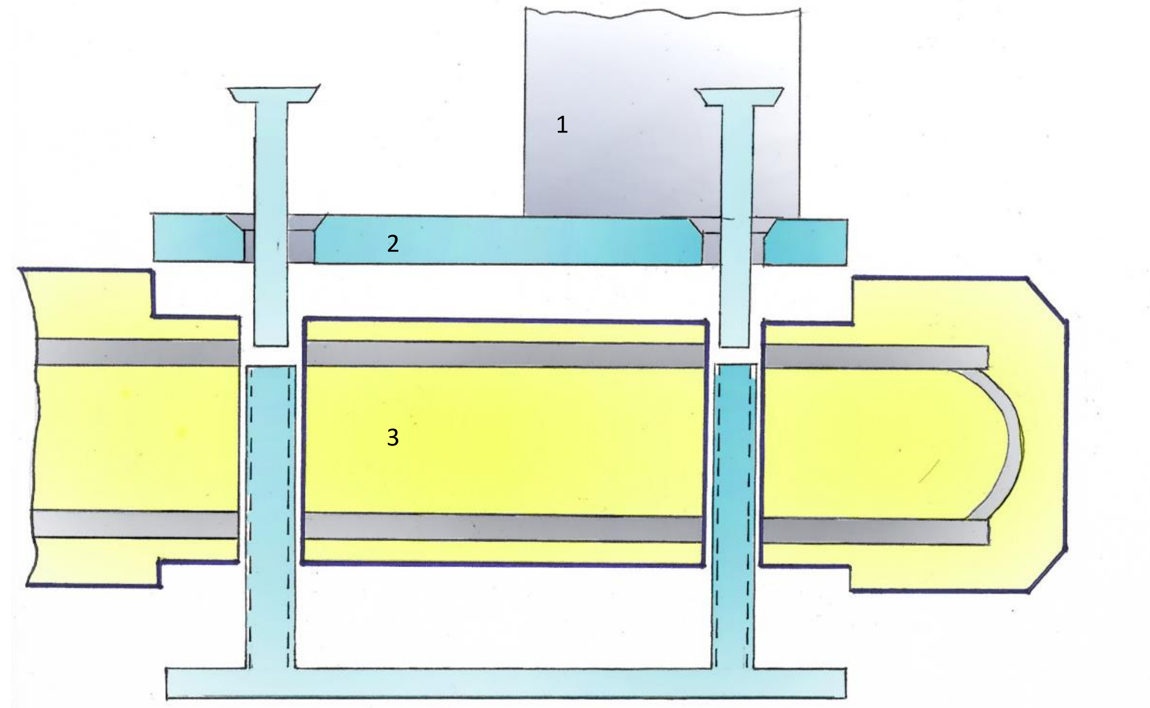


*Example cable stay geometry and load

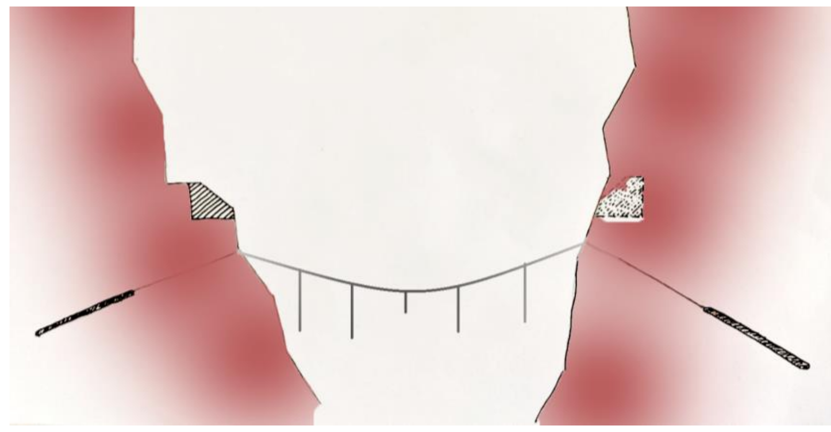
Inspirational projects and ideas:
1) Warehouse with constant tension bottom chord (Maillart) and reciprocal diagram (Baker 2013)
2) Thin walk-on arch - Footbridge of Peace, Seoul
3) External tensioning bars - Pavilion of the Future, Seville
4) Feature UHPC Staircase - Somerset House, London



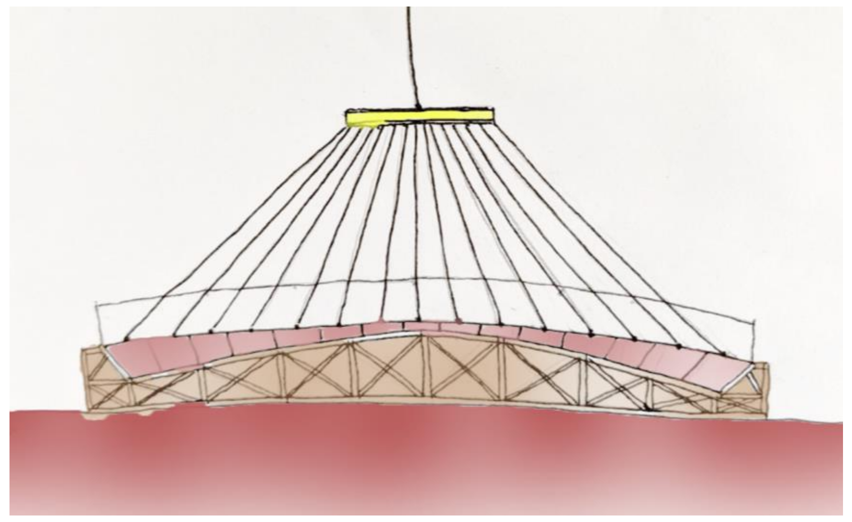
Above - View of typical UHPC voussoir:
1,2: Installed balustrade unit (N.B. balustrade continuous over several voussoirs), UHPC unit
3,4,5,6: Lifting eye, Decorative cap and connection to cable, penetration in UHPC unit, cable and termination
7: Extract of engraved pattern in deck to enhance water run-off and grip,
8: Exploded view of balustrade base



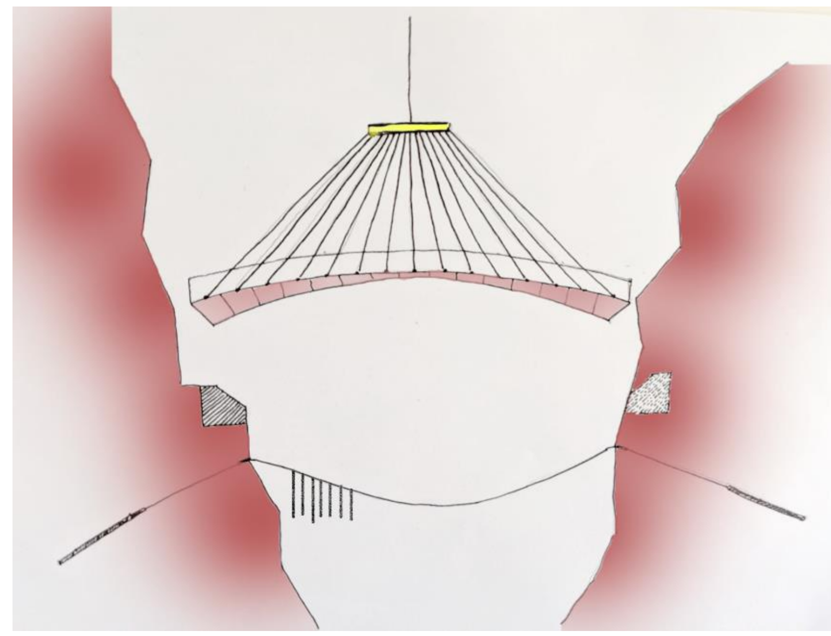
Above: check of critical detail at base of handrail:
Blue shows 'cut' steel, grey steel in elevation, yellow shows 'cut' concrete
1,2,3: bottom of handrail, clamping detail for base of handrail, UHPC with embedded reinforcement.
Maximum UHPC depth ~70mm.



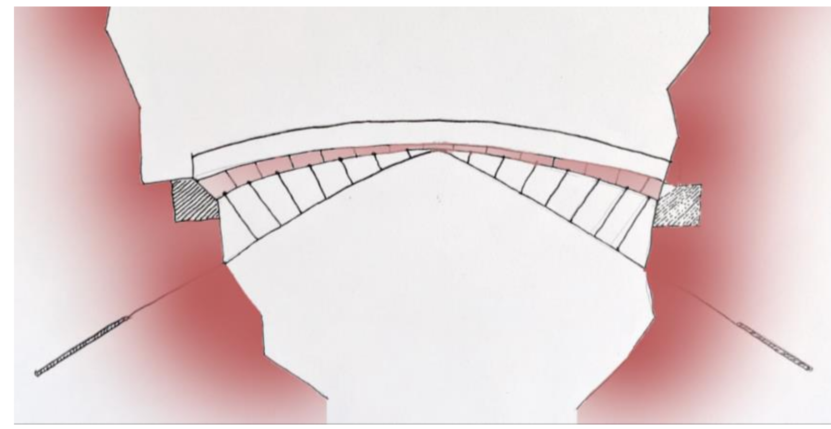
Construction 1: Install springers, rock anchors and cable from path or abseil, these are surveyed and end bridge voussoirs machined to suit.



Construction 2: Construct bridge and install balustrade on formwork at top of canyon, use penetration through each component as a lifting eye.



Construction 3: Using ~250T crane 15 back from edge of canyon lift bridge onto springers. Bridge stable under self-weight and is a safe working platform on installation (but avoid pattern loads)



Construction 4: Pull cable stays through lifting eye penetrations, progressively tighten the cable stays, grout up, and install decorative caps.

Response to the brief: From one view, this is a very challenging site due to its difficulty in access and narrow constraints presented by the cliffs on each site. Looking again, it offers immense opportunity, the excellent availability of supports means almost every bridge form is feasible. It feels perverse to not take advantage of the cliff faces' strength to reduce the required material in the bridge. It feels as if a pure tension or compression structure must be optimal in some way. In our case, two interlinked structures, one purely compressive and the other purely tensile, enable the arch to be pushed to its limits. We propose to colour match the UHPC and local stone to increase the sense of connection between the bridge and cliff faces that support it. This will use some local stone to help colour the UHPC, supplemented with dye as needed.

New materials and technologies: We have explored some opportunities offered by modern construction techniques – factory manufacture of UHPC voussoirs with non-planar faces, machined details where needed, high performance concretes – to reinvent one of the oldest structural forms.

Reciprocal diagrams: Graphic statics has been reinvented in recent years, with a computational approach (for example using Geogebra, Rhino) allowing the designer to explore the geometrical and force spaces simultaneously. For example, constraints such as springer bearing pressure (a force condition), maximum permissible gradient for visitors with restricted mobility (a geometry condition) and cable geometry (an aesthetic consideration) could all be considered, and satisfied, together.

As offsite as possible: The slimmed profile of the arch, resultant weight reduction and single lift moves work away from the high risk canyon path. Temporary works in the valley is eliminated with almost all assembly taking place at the plateau at the top of the canyon (or even in a factory). The only required working at the path level is for the two rock anchors and springers.

Disassembly: To remove the bridge, the construction sequence is reversed (cable stays removed, lifting eyes installed, bridge lifted out). This process can be used for maintenance if needed.

Funding and sponsorship: The decorative caps on the UHPC blocks over the stay cables offer an opportunity to acknowledge sponsors/friends of the park which is integral to the structure. Recommend: brass rubbing.

Team 17
IABSE FoD Design Competition 2019