Designing Wendover Dean Viaduct – A perspective on digital design tools, and simple hand calculations

Wendover Dean viaduct is a new bridge currently under construction in the C23 package of HS2, located within the Chiltern hills, just outside of Wendover. It is 450m long, with 8 equally spaced main spans and 2 shorter side spans. The deck is a double composite ladder deck (principle shown in the figure below). COWI were awarded the design of both this viaduct, and the similar Lower Thorpe viaduct. I was the principal designer for the superstructure for both.

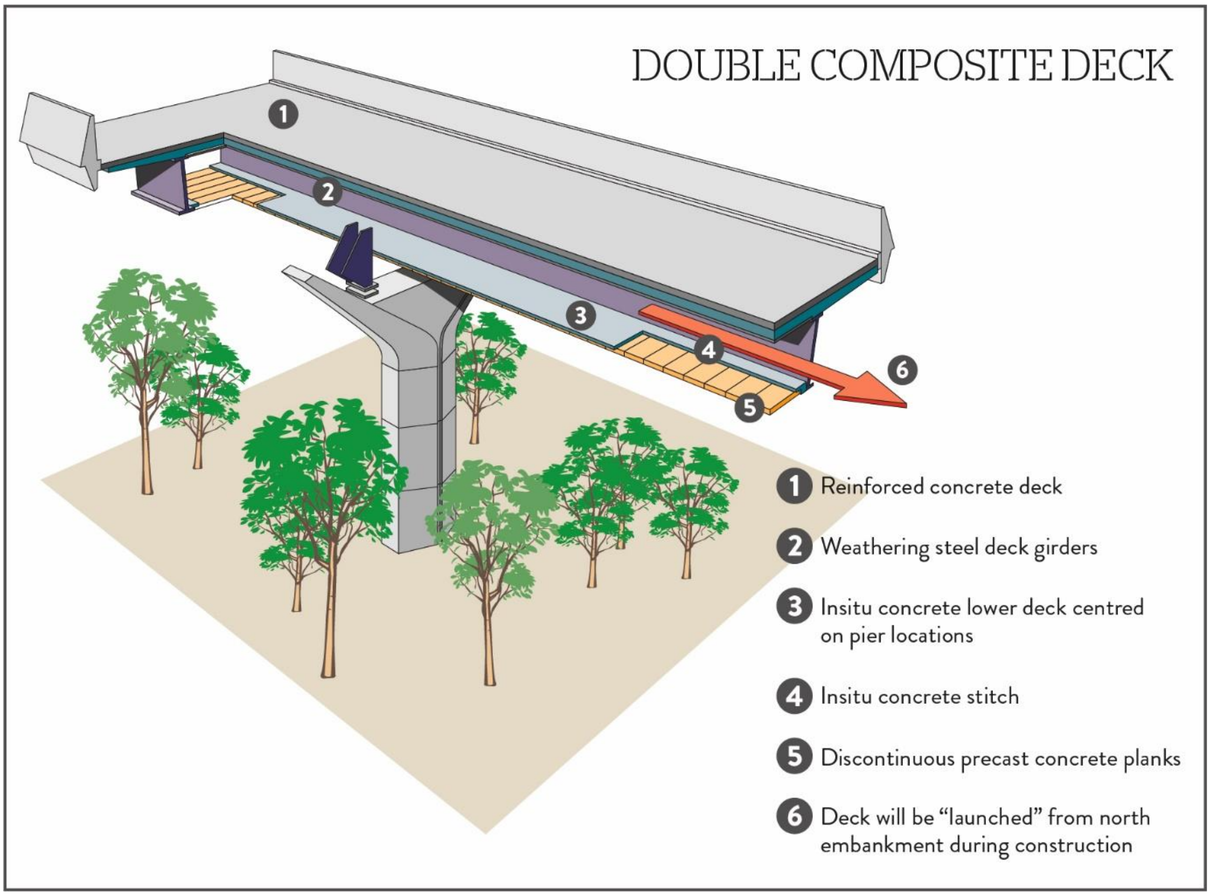

Figure 1: Schematic showing the form of the double composite deck adopted on Wendover Dean viaduct. Image Credit: https://www.newcivilengineer.com/the-future-of/future-of-bridges-hs2s-french-inspiration-for-chilterns-viaducts-13-11-2020/

In this paper I've chosen to concentrate on the use of digital tools in the design process of Wendover Dean, and the advantages they brought.

The thorough requirements of high-speed rail suited the creation and application of several digital design tools in Python, and the fact that there was a pair of similar structures being designed gave confidence that the investment of development time would be well spent.

An argument often made against use of digital tools in engineering projects is their "black box" nature, and that the output is hard to check. I will cover how simple "back of the envelope" hand calculations can be applied alongside sophisticated analysis methods to increase confidence in results. I also show example of the rich outputs that can be generated as part of these tools, which can also be used to interrogate results; a key part of the quality assurance process.

Speed

When completing hand calculations, or doing a computationally expensive calculation, engineering judgement needs to be used (e.g. to predict which loadcases will be critical to the design of a particular element). The speed of digital calculation tools can allow for many cases to be analysed quickly and confirm if the result predicted by engineering judgement is indeed critical.

Dynamic performance is often a key driver for high-speed rail structures, with strict limits on the deck acceleration. For HS2 structures there was a requirement to analyse several load models and a large range of possible speeds. A time stepping dynamic analysis on even a simple finite element model is unfeasible for this large number of cases due to the time & memory requirements. Therefore, a Python tool based on multi-modal responses was used to analyse the dynamic response instead in a fraction of the time.

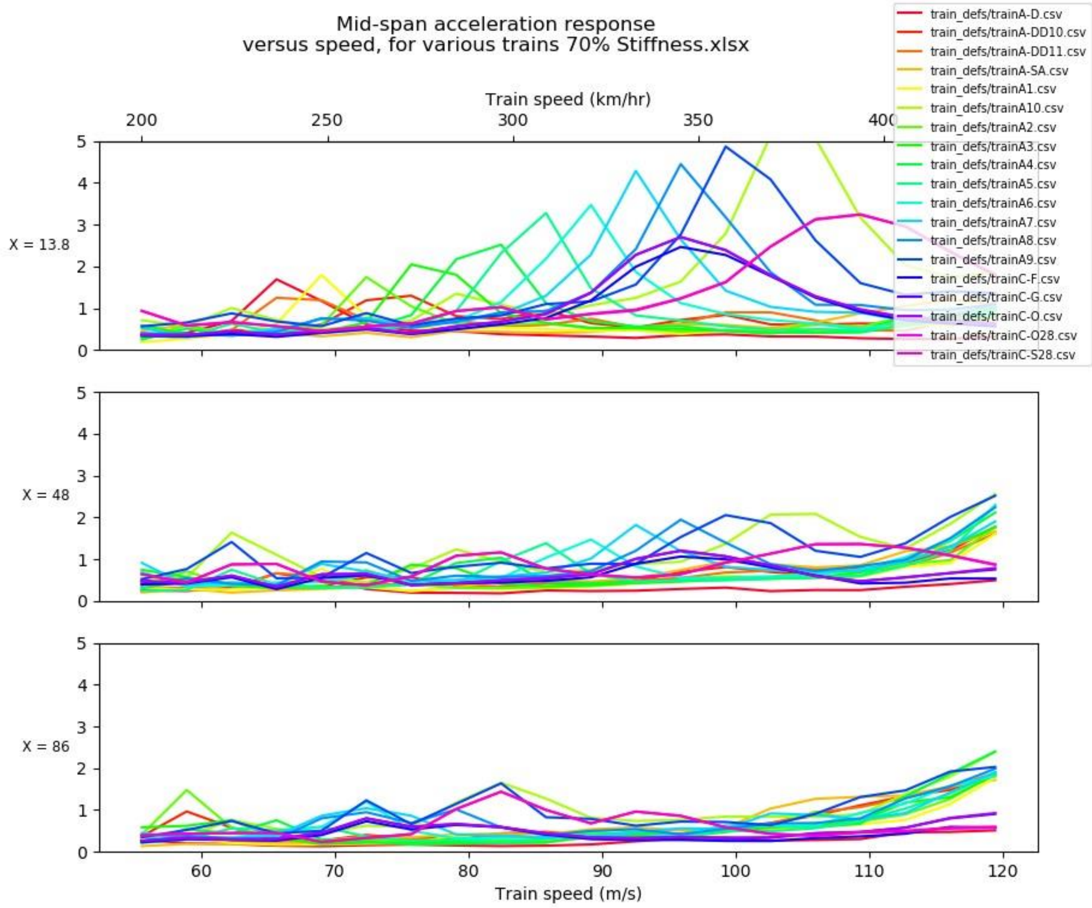

Figure 2: Acceleration results from dynamic analysis

In many cases the response is dominated by a single eigenmode of the deck. It is then relatively simple to perform a verification using a selected speed of a train for a given axle spacing, to effectively get a pulsating load at the natural frequency of this mode. It is then simple to either do a single degree of freedom hand calculation from static results or check this critical combination using a full time series analysis using finite element methods.

Repetition

The ability to repeat calculations by just changing the inputs and re-running the analysis is a key part of why digital tools are useful in the design of structures, which naturally adopt changes throughout the design process.

As with many rail bridges, fatigue was a key driver in the design of Wendover Dean. It affected steelwork sizing on certain elements (such as the bottom flange), and the extent of the structure to which a higher quantifiable service category was specified, which puts more onerous requirements on the fabricator.

The analysis method using LM71 envelopes with damage equivalence factors was found to be conservative when compared to using the reservoir method with predicted HS2 load models.

These fatigue calculations were well suited to being automated, due to their repeatability and the large number of inputs that needed to be considered. These varying inputs included 13 different train load models, multiple possible train lengths and number of cycles to consider and 2 tracks on the bridge with possibilities of either or both being loaded.

The automated calculation process produces a full set of interrogable results in HTML format, so it could be viewed as a webpage with overall summaries, and the ability to view a detailed calculation for any individual part.

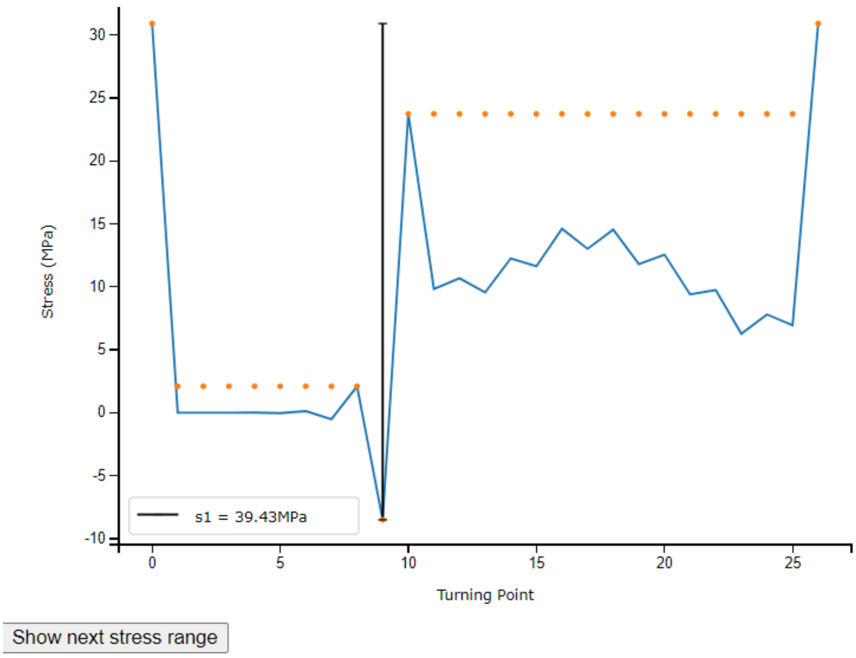

Figure 3: An interactive plot from the output of the fatigue calculation for a single location for a single loadcase

A simplified hand calculation can be carried out based on a few assumptions. These were that the heaviest provided load model would govern, the single largest stress range will dominate the calculation, and some simple assumptions on loading of each track/number of cycles etc. By doing this simple calculation, confidence can be gained in the results from the detailed analysis by getting a similar answer, while also knowing that the more complex analysis will cover some of the potentially unconservative assumptions made.

Precision

When designing using digital tools, the increased precision that can be achieved allows designs to be less conservative than simplified hand calculations normally achieve, but the added complexity in the analysis can make it harder to spot mistakes. Output from analysis tools can normally be checked with an extremely quick back of the envelope calculation to a reasonable level of accuracy, ensuring that the tool has been used correctly.

A well-made spreadsheet can make a hand calculation simple to repeat for a certain number of variables, and can be quick to implement, but still come with many of the dangers of errors being hard to spot without a well explained and checked outputs (while also dealing with the limited visual output of excel).

On Wendover Dean, the majority of the superstructure design was completed with such a spreadsheet, where key simplifications had to be made on e.g. the geometry of the section, but it then led to an easy to use and repeatable tool for a large number of the flexural design checks.

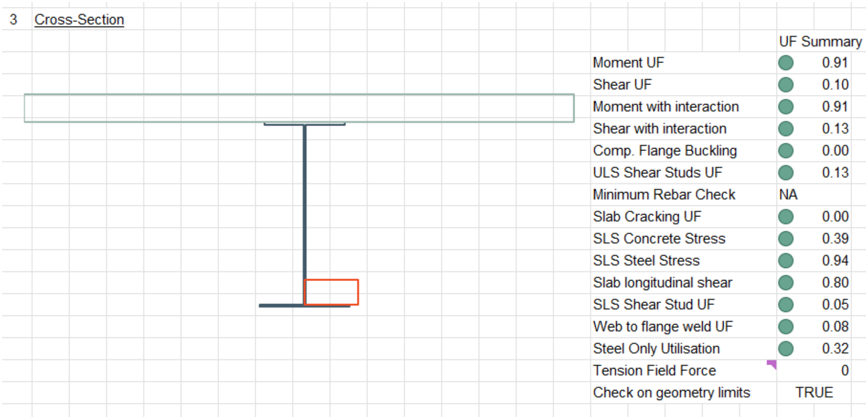

Figure 4: Snapshot from the double composite design spreadsheet. Note the simplified geometry.

From the output of this spreadsheet, it was easy to see where more attention to detail was required, and a more precise analysis needed. A sectional analysis tool developed in Python could then do a more detailed check with the exact geometry and material behaviour modelled to achieve a more efficient design.

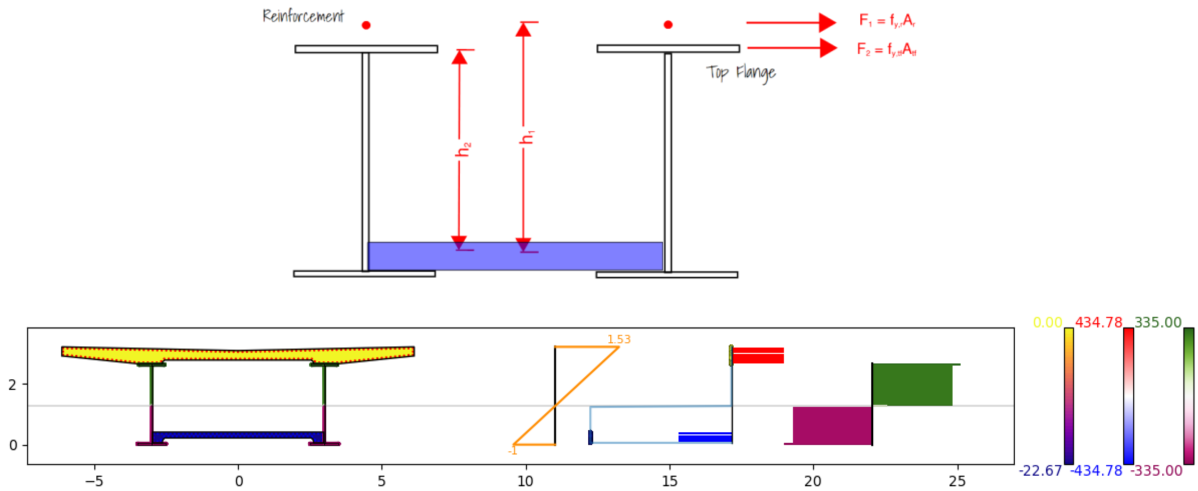

Figure 5: Example of a quick calculation being able to approximate a more precise equivalent. For this example taking an approximate lever arm and the plastic capacity of the reinforcement & top flange estimates the moment capacity of the section to within 10% of the detailed calculation.

Visualisation

By employing the mature plotting libraries available within Python, calculation outputs can be incredibly flexible to the needs of the user. This means that plots can be produced to view large sets of data very succinctly.

As part of my role in the design of Wendover Dean, a full detailed launching analysis (including precamber, friction etc.) was carried out. This produced a very large set of results, that can be hard to analyse and interrogate, but with the use of multiple plots it was possible to compare results easily. Animations also led to a way to easily communicate the structural behaviour and see results for specific stages.

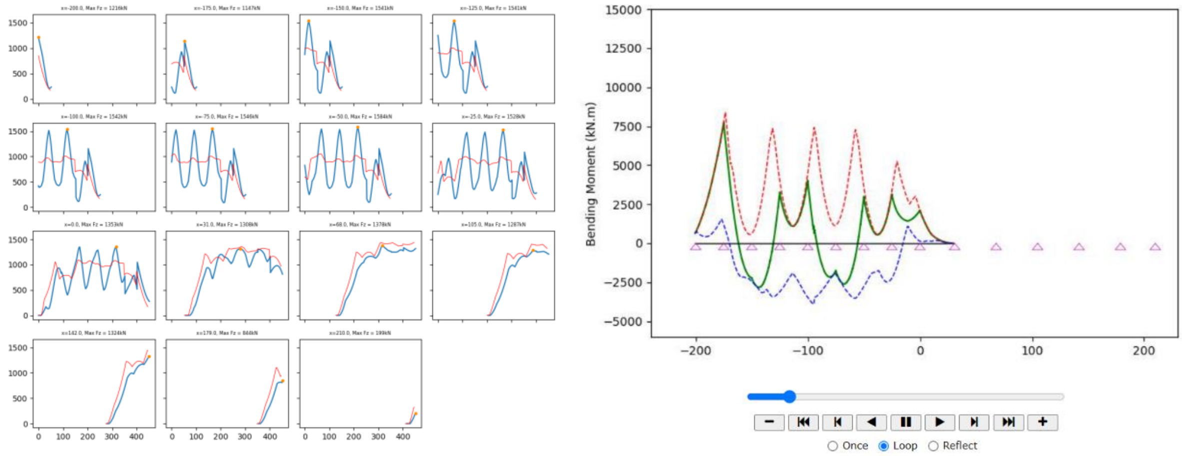

Figure 6: Sensible plotting of results throughout the launching stages allowed for a large amount of data to be displayed in compact forms, and animations allowed for the information to be easily understood and interrogated.

Conclusion

Digital tools can be used in the design process to provide powerful ways of performing calculations quickly, with high levels of repeatably and precision, and produce rich output visualisations but should be treated with care and the outputs carefully interrogated. This can often be done by simple hand calculations to produce an efficient design workflow, with high levels of confidence in results.