# An introduction to bridges for structural engineers (part 1)

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**Synopsis**

**This paper is the first of a two-part introduction to bridge design for structural engineers. Together, the two parts identify nine major issues relating to bridges, of which structural engineers more familiar with building design should be aware. Part 1 addresses construction, aesthetics, value, environment and loads; while Part 2 will cover materials, elements, effects and detailing.**

**The papers make the case for bridge design to be overseen by a *single guiding hand* – an experienced and creative bridge engineer with a wide range of social, visionary and technical skills.**

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**Figure 1**
**Blackwater Viaduct (Ireland) – launching construction**

## Introduction

There are a number of key issues that are not always seen by structural engineers, but which are very important for bridges. There have also been a number of concerns (including failures) around the world recently, many of which have raised common themes about the structural integrity of bridge design and construction.

With failures, for example, collapses often occur during construction and are caused by a series of events, never just one. Collapses during service are rarer, but are generally caused by poor maintenance regimes adversely affecting critical joints. While looking at these collapses, it has become apparent that the crucial issues are related to the construction process and its supervision, poor design and detailing, new solutions, and inexperience of the team.

Failures always affect the public psyche too, as bridges are so well liked and remembered by people, much more so than most buildings. Not only do bridges show a sense of drama, but also, in having their structure exposed, they are better understood. They are intrinsically seen as links between communities and across divides, making them very comforting and familiar.

This paper is aimed at structural engineers, but also serves as an *aide-memoire* for civil engineers. It refers mainly to traffic bridges, which need to last over 100 years, be virtually free of maintenance and justify their existence using public funds. It does not directly cover footbridges, as they are different to other bridges, being more akin to buildings, sometimes with a shorter lifespan and less concern over long-term integrity, and frequently privately funded too.

I am not saying that structural engineers should not get involved with bridges, but simply that bridges include many aspects that are not common in buildings. The nine major issues identified are: construction, aesthetics, value, environment, loads, materials, elements, effects and detailing.

Part 1 describes the first five issues, while Part 2 will conclude with the final four issues and a summary that the best bridge engineers should carry a wide range of skills and experiences, in the true sense of Brunel – engineers who are technically strong, creative, visionary leaders, who can carry the owner and all stakeholders to a solution of the highest quality and greatest value.

## Construction

Whereas the precise construction method need not be a concern in many buildings, the same cannot be said for bridges. Nearly all bridges cannot (and should not) be designed without good knowledge of the construction method and its temporary stages[1–3]. The construction method will generally have a major effect on the design. In selecting the best solution, the engineer should choose a method as well as the design layout, as they are fundamentally entwined.

Each method will produce different spans, layouts, sections, depths, thicknesses and details. A bridge built by launching (Figure 1) is completely different from a bridge built span by span or from one built in balanced cantilever. Not only are the stage-by-stage forces very different (and significant), but the locked-in forces are also different and significant.

Each method is built using a variety of pieces of falsework, each of which impacts upon the permanent works differently. Erection cranes, scaffolds or props, girders or gantries, shear legs or lifting frames, and noses or tails all have varying effects upon the temporary stages, and upon the permanent set of locked-in forces (Figure 2).

These temporary effects (on temporary and permanent works) are often larger than any long-term condition. As the loads are generally caused by the self-weight of the bridge, the loads are real, as opposed to the theoretical service loads that bridges may never experience. As a result, great care has to be taken to ensure the safety and integrity of the temporary and permanent works at all stages.

The ownership of the design at each stage is imperative – the best option would always be that a *single guiding hand* from the designer oversees the design and construction (D&C) process through all its stages. Not only does it ensure that the engineer can implement a design vision, it also ensures that the same engineer can oversee all the permanent works (in all its stages) and, indeed, all the temporary works too, which all guarantees that good value is carried throughout the project. As soon as this continuity of ownership is broken (having different engineers on board), care needs to be taken to ensure that the design is correctly owned at all stages.

Many continental contractors are extremely strong technically, much more so than many UK contractors, who have become stronger in management. The vast majority of major bridges in the UK over the last 25 years have, indeed, been built or led by continental contractors, who can manage many risks and innovations more successfully by being strong technically. Their technical departments would often be larger and more experienced in design than many UK consultants.

So, a UK contractor more experienced in subcontracting might prefer bridge solutions that suit this background – being drawn towards steel solutions produced by fabricators or pretensioned beam solutions produced by precasters. However, a continental contractor (or other technically strong UK contractor) would generally consider a wider range of steel and prestressed concrete (PSC) options.

Ultimately, if a contractor has an estimating, programming and technical team that can consider many options, it will; whereas if it has a team with limited experiences, then it will only price successfully those solutions for which it does have experience. De facto, the bridge solution that emerges will often be determined by the experiences of the contractor, not the consultant.

## Aesthetics

Whereas the appearance of the structure in a building is generally hidden, the structure of a bridge is entirely on view, as it should be. Buildings are clad to protect the occupants and therefore the structure too. Bridges have no need to be clad, although there are a few rare exceptions, such as the towers of Tower Bridge, which are steel frames clad in stonework. Bridge structures should stand proud and be designed entirely with that in mind. It is noted in the *Environment* section that bridges can readily be made with structures that can withstand over 100 years of weathering, and thus cladding never makes any sense.

Referring to Vitruvius's *De architectura*, the three principles of *firmitas, utilitas* and *venustas* can be seen. *Firmitas* is the attribute of durability and robustness – a given for any structure. *Utilitas* is the utility, or function of the structure, i.e. the wise use of the owner's money. *Venustas* is the beauty, or form, i.e. the elegant structure that enhances the built environment and delights society. This is the classic balance between form and function.

Ideally, this balance at the early stages of design should be held within the mind of a


Figure 2 Stratford Bridge (London) – arch construction

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Figure 3 Salginatobel Bridge (Switzerland) – arch aesthetics

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Figure 4 Humber Bridge (Yorkshire) – catenary aesthetics

*single guiding hand* – the same *guiding hand* referred to in the *Construction* section. This bridge engineer should have a thorough grasp of the aesthetic ideals, related to context, scale, lines, balance of mass and void, and good proportions. This engineer should have the vision and leadership to drive an elegant solution through to delivery.

Most bridges are dominated by their engineering and environmental challenges, and it is nearly always the resolution of these issues that defines the beauty and success of the bridge. Generally, solutions that are designed to suit the flow of forces will tend to have a natural elegance, with that flow being an expression of strength and stability.

All public surveys of bridge design tend to show that most people are drawn towards arch structures[4], as they are recognisable as being safe, soothing and elegant (Figure 3). Equally, suspension structures have the same feel to the general public, albeit the typical spans are much larger (Figure 4). It is no accident that the vast majority of ancient bridges were indeed either arches or catenaries.

Beams, whether of constant or variable depth or trusses, are often seen as being unsatisfactory by the public, as even though everyone knows that they work, most do not understand how they work. However, beams are often the most effective construction (and, therefore, value) option, but they must all still be designed with care for the aesthetics (Figure 5).

Interestingly, cable-stayed bridges often split opinion. Many like the extreme thinness of the decks and the almost invisible cables, but are perturbed by the lack of understanding as to how the bridge works. In the engineering community by contrast, cable-stayed bridges are invariably well liked, as we understand them[5].

**"SOLUTIONS DESIGNED TO SUIT THE FLOW OF FORCES WILL TEND TO HAVE A NATURAL ELEGANCE"**

The role of architects in this aesthetic process can be a welcome addition, as long as the architect is skilled in bridge design and respects the considerable forces at work in a bridge. Architects can also bring a wider appreciation of the social and environmental issues, but the type of engineer described above must remain entirely in control. It is worth remembering that the vast majority of the world's most fabulous bridges had no independent architectural input, or any additional architectural premium applied to them.

All bridges should be fine pieces of engineering of the highest quality, including aesthetics, and this can readily be achieved without any additional architectural features or costs. The skilful engineer who is well aware of the aesthetic demands of the scheme should select the best option for the owner, and stakeholders, and also be aware as to when independent architectural input might be valuable. D&C projects are equally able to produce wonderful solutions, as none of the aesthetic parameters outlined above would tend to add any significant cost to a well-designed bridge[6,7].

## Value

In a building, the structural content might only be 20% of the total cost, and as such the architect tends to lead the design and the engineer supports the team. However, in bridges, where the structural content might be 90% of the total cost, the engineer must lead and an architect, if needed, should provide support. Bridges are therefore much more dominated by their structure, and its cost, than any building (with its mechanical and electrical (M&E), and architectural costs). All engineers must be familiar with the costs of their project, but bridge engineers must be much more familiar, as every decision taken from the early stages will have an impact upon value.

As noted in the *Construction* section, the design of most bridges is heavily influenced by the construction method and scale of the project, which dominate the programme and directly affect costs. In order to make good decisions about the most appropriate bridge type and span, the engineer must understand these various methods, and indeed, the selection of a particular method will then define the bridge type and span.

It is surprisingly easy for a skilful bridge engineer to produce costs for different bridge types, as there are good data available for a breakdown to be produced[2,8,9]. Such data are not required to determine an exact project cost, but to select which out of several good options might be the most effective. In this case, engineers can use

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Figure 5 Clackmannanshire Bridge (Scotland) – beam aesthetics

overall rates for concrete, reinforcement, prestressing, steelwork, formwork and falsework to get a total structural cost. These overall rates must include for materials, as well as allowances for the method-related labour and plant costs.

It is clear when working with such figures that the most cost-effective bridges are ones that can be built quickly, as well as easily and safely, i.e. speed of construction will generally determine the best option. This importance of speed applies to rural or coastal sites (where mechanisation can reduce labour costs), and to schemes in the urban environment, where reduction of traffic management or possession costs can be dominant.

As most bridges are public structures, the term *good value* not only relates to costs, but also to the needs of the owner, quality, aesthetics, the integrity of the design over the life of the bridge, environmental impact and the needs of society. This is a wide set of demands that a skilful engineer must keep in mind at all times. As part of the cost assessment, the bridge must be made as durable and free from maintenance as possible. It is not always necessary to drive material quantities down to reduce costs, as the selection of the best construction method is much more likely to be a critical factor.

The increasing use of finite-element (FE) analyses should certainly be applauded, if

**"THE MOST COST-EFFECTIVE BRIDGES ARE ONES THAT CAN BE BUILT QUICKLY, AS WELL AS EASILY AND SAFELY"**

used wisely. Ultimately though, fine tuning the final few percent of an analysis that can only ever be an approximation to reality, is an illusion of accuracy, suggesting a greater degree of precision than can ever be the case. At the stage of producing drawings, for example, the engineer might only have to choose between a B16 or B20 bar, which is over 50% larger. The key is whether the overall solution is correct, not the *minutiae* of the analysis. It is best not to ponder excessively on individual code clauses, complex 3D analyses or multiple spreadsheets, but to concentrate on good solutions and details, which can be built safely, easily and quickly, often on cold, wet

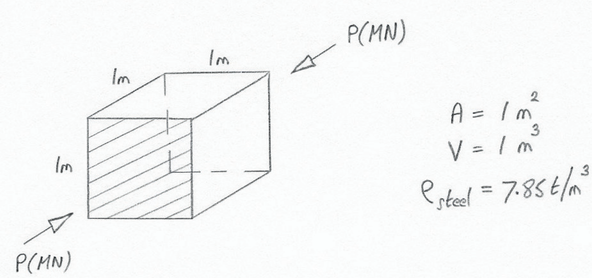


Figure 6 Simple bridge – material cost comparison

| | approx SLS stress (MN/m2) | Force P (MN) | Overall Cost Rate | | Cost (£) | approx Cost/Force (£/MN) |
|---|---|---|---|---|---|---|
| **Concrete** | 12.5 | 12.5 | 500 | £/m3 | 500 | **40** |
| **Reinforcement** | 250 | 250 | 900 | £/t | 7,100 | **30** |
| **Prestressing** | 1,000 | 1,000 | 2,500 | £/t | 19,600 | **20** |
| **Steelwork** | 200 | 200 | 2,000 | £/t | 15,700 | **75** |

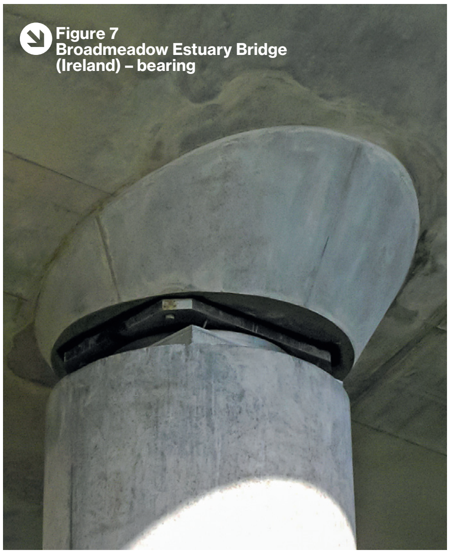

Figure 7
Broadmeadow Estuary Bridge (Ireland) – bearing

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and remote sites[8].

As noted in the *Construction* section, the bridge solution that emerges will often be determined by the experiences of the contractor, not the consultant. A team more familiar with steelwork will select that option, whereas a team more experienced with prestressing will tend to choose PSC options.

Much debate can be had about the suitability of various concrete or steel bridge rates, but nevertheless it is still possible to see which materials are most economic in carrying basic loads. Simple calculations show that it is twice as cheap (in £/MN) to carry compressions in concrete than in steelwork, which is why bridge deck slabs and piers are invariably concrete (Figure 6). The same calculations show that prestressing strand is cheaper than reinforcement, which is why it is better to use PSC bridges than reinforced concrete. Reinforcement is also twice as cheap in tension as steelwork, which is why as much as possible of the top tension in a continuous composite deck should be carried by reinforcement.

Actually though, it is the method of producing the webs that determines the overall solution – PSC bridges have concrete webs and thus use prestressing throughout, whereas composite bridges have steel webs and thus use steel flanges, albeit some are composite. The best solution might be for a hybrid system with concrete compression flanges, steel webs and prestressing carrying the tensions, which is similar to some innovative schemes seen outside the UK recently.

## Environment

Whereas most buildings are clad, and are therefore protected from the elements, bridges are very rarely clad (and should never be) and are thus always exposed to the environment – the two key components being sun and rain. The net result is that bridges undergo significant temperature changes and have to accommodate large amounts of water (often salt-laden). They have to remain durable under these conditions for at least 100 years, which makes them very different to nearly all building structures.

The axial changes in a bridge due to temperature give rise to movements of up to ±400mm. Any concrete in a composite steelwork section will shrink, while concrete in a PSC member will also undergo elastic shortening and creep. These effects are of a similar order of magnitude to the temperature movements, and thus add significantly to the total. The result is that all bridges must be designed to accommodate these movements. If movements are allowed, then the bridge has no resulting axial stresses, whereas if they are restrained, the bridge will pick up stresses. Bridges over about 60m in length will have bearings at most support positions. These bearings need to carry the vertical (and lateral) loads from the bridge down to the substructure, while allowing the bridge to move longitudinally (Figure 7).

As well as resisting lateral loads, bridges also need to be held firmly against longitudinal loads. As a result, while the majority of bearings will allow longitudinal movement, some do need to be fixed against it – it is at these *fixed* bearings that the longitudinal loads from traffic, wind, impact or differential friction are carried.

Bridges with lengths less than about 60m should be designed as integral structures, wherever possible, i.e. with the elimination of bearings, as bearings are a maintenance burden, needing to be replaced every 25 years or so. Integral bridges carry all loads directly in the structure and accommodate movements through the use of various flexible structural solutions.

Integral piers can still be used on bridges over 60m, as long as there is enough flexibility in the system (Figure 8), but eventually it becomes impossible to accommodate the larger movements and bearings must be incorporated. So, whereas in buildings the stability is usually provided by a selection of staircase or lift cores, bracing or shear walls, in most bridges, the stability is provided by *fixed* or *guided* bearings acting on rigid piers or abutments.

At the ends of bridges, there is a need for expansion joints between the bridge and adjacent structure. As these joints are a significant maintenance burden, and as much of the distress that has been seen historically (including some collapses) does indeed occur at joints, it is always best to limit their number. Single lengths of bridge can be 1500m long without intermediate joints; therefore, it is common to use

Figure 8
River Dee Viaduct (Wales) – integral piers

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**Figure 9** **Stratford Bridge (London) – weathering steel**

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continuous bridges, wherever possible, i.e. to avoid simple spans with multiple joints[3,10]. The only exception is on railways, where structural joints are generally incorporated at about 80m centres, to avoid expensive joints in the rail.

As noted at the start of this section, rain (or water ingress) has a major impact on bridges, especially those where road salts are used as a de-icing material. This corrosive water needs to be kept well away from sensitive bridge details, especially joints and connections. This is achieved through the use of well-detailed deck waterproofing membranes, together with a series of drips, falls, gullies and pipes to carry the water away.

The structure itself will usually be exposed to salt-laden spray, and thus both concrete and steel surfaces need to have adequate ability to survive for many years. Concrete can be specified to be maintenance-free for over 100 years by the appropriate use of cement content, water-to-cement ratio and cement type to define the correct cover to the reinforcement[2].

The latest range of sophisticated paintwork systems for steelwork can provide 20 to 30-year lives before major maintenance is required, although it is increasingly common to use weathering steel (Figure 9), which can also be maintenance-free for over 100 years, as long as it is detailed to avoid excessive exposure to salt spray[3].

Most bridges in the developed world undergo a structured routine of regular inspections and maintenance, although global failures clearly highlight that the costs of maintenance do prohibit many owners from implementing thorough regimes. The performance of bridges must be continually monitored against any changes in use, or any increases in loading or reductions in strength due to deterioration that has not yet been repaired or strengthened. Regular visual inspections are supplemented by more detailed assessments or testing regimes as the bridge ages; on larger bridges, instrumentation can be installed to allow real-time monitoring. This proactive management of bridge stocks is essential, as well-maintained bridges are not only more economic but also safer. With such maintenance regimes, bridges can be expected to last well over 100 years[3,11].

There are several environmental effects that do not affect bridges at all. Snow is never an issue as traffic load intensities are considerably higher, and fire is rarely a concern as there is nothing in the majority of bridges that is combustible. There is also very little M&E input on most bridges; certainly nothing like the scale seen in buildings, albeit the interfaces with M&E and control systems are a major consideration on moveable bridges.

> **"CORROSIVE WATER NEEDS TO BE KEPT WELL AWAY FROM SENSITIVE BRIDGE DETAILS"**

The only other important environmental effects are related to wind and earthquakes. Static wind loads should be included for all bridges, but it is only for the very longest or most slender structures that any serious dynamic assessment needs to be carried out. Nearly all beam or arch bridges will not fall in to this category, whereas nearly all cable-stayed or suspension bridges will need to be assessed for wind-related resonances.

Seismic effects can affect all bridges, just as in buildings, but most bridge superstructures are rarely sized by them, as traffic loads are more dominant. However, bridge bearings and substructures can be significantly sized by seismicity, in areas of the world where you would normally expect to find such issues.

## Loads

Traffic loads on bridges are not only larger than in buildings, but also more concentrated. Whereas in buildings the typical loads might be 2–5kN/m², the standard uniform load in bridges is around 5kN/m² for footbridges, 10kN/m² on highways and 10–30kN/m² on railways, depending on whether the trains are light or heavy metro, or full size (Figure 10). The concentrated loads that can be applied almost anywhere on the bridge deck relate to vehicles or locomotives weighing 100–200t – these vehicles produce large axle and wheel loads that can be critical for local and global effects on the bridge deck.

As the loads are larger, more concentrated and can be positioned almost anywhere, it is common to use influence lines or surfaces to select the worst load positions that create the peak effects. Although the stiffness analysis of line beams and 2D grillages (or frames) can adequately predict the self-weight and traffic loads for most bridges, it is increasingly common to use 3D space frames or FE analyses. As with any structure, the engineer should be able to, firstly, carry out an analysis by hand; secondly, carry out a simple computer analysis with line beams or 2D models; before thirdly, carrying out a final, more complex 3D analysis to hone the details.

The eccentricity of these large concentrated loads also produces significant torsions – torsional loads are not usually seen in buildings, or can be ignored in the plastic design that is generally used. For deck sections with multiple girders, the result is to determine which girders carry the peak loads, but for box-girder decks, the result is significant torsions that also produce torsional and distortional warping. These warping effects can be analysed with charts and tables, or can be assessed with various FE analyses. The warping stresses are elastic and incorporated into the design of non-compact steel boxes at the ultimate limit state (ULS) and PSC boxes at the serviceability limit state (SLS).

Bridges also have large horizontal forces from the vehicles they carry, both laterally and longitudinally. Braking, traction, nosing and centrifugal effects can all produce large loads on the substructure, although they tend not to have a huge effect on the decks. Impact loads from vehicles are also important, both on the deck and piers. In extreme, marine piers of large bridges are designed to carry ship impact loads that can be 20–100MN.

As in buildings, the imposed loads on medium-sized structures might be similar to the self-weight loads. However, on small bridges (10–20m spans), traffic loads will become more dominant, whereas on large bridges (60–2000m spans), the self-weight becomes hugely critical. In these cases, the key design factor is to reduce self-weight. This is why larger bridges in concrete are highly tuned with profiled slabs to reduce thickness and why the most efficient PSC girder is a single-cell box with two webs. Equally, larger bridges in steel start off using stiffened webs and composite top flanges (which are economic) and eventually become sections made entirely from orthotropic steelwork, i.e. with stiffened webs and flanges throughout. All these types of more complex section need a greater understanding of structural behaviour than simple beams.

It becomes clear when working on bridges that the best units to use are often MN and m. Most loads and shears are best expressed in MN and bending moments are commonly in MNm, while section properties are sensibly given using m² and m³. The net result is that stresses come out in MN/m², which is the same as N/mm².

## To be continued...

Part 2 will cover the final four issues – materials, structural elements, structural effects, and detailing – as well as presenting overall conclusions.

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**Figure 10** STAR rail viaducts (Kuala Lumpur) – metro train loads

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