The Coy Mistress – a view of masonry behaviour

Based on his 2012 James Sutherland History Lecture and drawing on a range of examples, Dr Bill Harvey (BSc PhD CEng FIStructE FICE) illustrates the difficulties of predicting masonry behaviour.

In May 1943, a bomb dropped in London Road, Brighton. It did not go off immediately but skidded along the road until it hit the railway viaduct. There it destroyed one pier (Fig 1), bringing down the better part of two full spans. Contrary to expectations, the rest of the viaduct did not follow in domino fashion. The adjacent piers certainly leaned into the gap and cracks up to 150mm wide opened in the spandrel walls of the adjacent spans[1].

The rubble was cleared, trestles erected with struts to hold the piers and jack them back to plumb. Way-beams were installed to carry the trains and the line reopened. The brick pier was then rebuilt, new arches created above and the temporary works removed. If you go to London Road now, the only real indication is the lack of shrapnel scars on the replaced pier.

There are many lessons to be drawn from this, not least the fact that modern engineering, hidebound by Quality Assurance would need a war to return to similar levels of courage. But the lessons about analysis and response to damage are more important. The question is not so much: “why did it not fall down?” but “how did it stand up?” This requires a completely different approach to analysis, though simple calculations remain the best way forward.

So, why did it not fall? A simple analysis of the bridge under dead load, with one span

Figure 1 London Road Viaduct. Partially destroyed by a WWII bomb

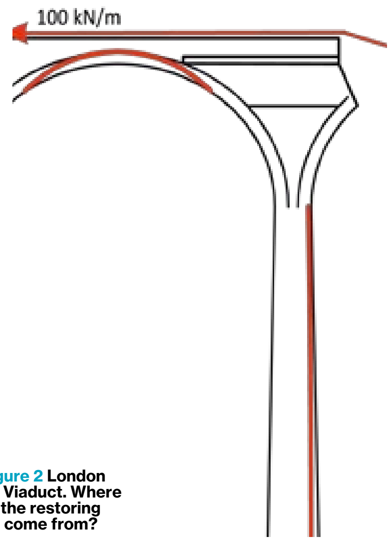


Figure 2 London Road Viaduct. Where does the restoring force come from?

Figure 3 Postcard showing a damaged viaduct at Hirson, Northern France c.1915

Figure 4 St Marks Belfry Venice. Rebuilt after collapsing in 1906

Figure 5 Church tower collapse, Belgium. Typical example of brittle failures. Note cracks (inset right)

Figure 6 Flying buttress above the retrochoir roof. Wells Cathedral

removed says that the pier is completely unstable.

Fig. 1 shows the railway tracks to be visible, still in place across the gap. Fig. 2 shows the effect of a restoring force at deck level where 100kN/m width is ample to prevent the pier tipping. The only source for such a force is the railway track. The bridge is about 9m wide so the total force required is 90t. There are six rails including check rails on the inside of the curve but not including the power rails which are ineffective. That means 15t per rail. The capacity of the rails is ample. Transfer to the bridge is less obvious but there are two paths. The first is through the sleepers and ballast. The second results from the kink in the rails at the broken edge as they sag in the gap. The load is, of course, carried back to the abutments in tension not in compression in the suspended rails. We should also recognise that the behaviour observed in Brighton is by no means unique (Fig. 3).

Where is this taking us?

This is but one example of how masonry can behave better, often much better, than modern engineering thinking leads us to believe. There are good reasons why engineering education (largely targeted at new construction) and even engineering practice leads to a false impression of what constitutes safety on the one hand and lack of it on the other. I hope to go some way to showing how this happens and how we might set about thinking more clearly about the behaviour of masonry. But let's begin with a bald statement. If the structure is standing and the sums say it shouldn't, either you have done the sums wrong or (more likely) you have done the wrong sums. In either case there is demonstrably no connection between the calculations and reality.

Redistributive behaviour in masonry

It is said, that a structure will not fall down until it has exhausted all possible ways of standing up. This is as true of a masonry structure as it is of any other. The big difference when dealing with masonry is not the material properties so much as the way they are assembled. Most masonry elements are either interconnected (notionally two dimensional) continua or completely three-dimensional lumps. They are also usually extremely stiff when compared with their foundations or with modern structures.

Ted Happold[2] was fond of saying that 'All structures are systems of interconnected stiffnesses'. At any moment, force will flow through the stiffest path, but the stiffest path may change with time and in very stiff structures the changes and their effects may only be obvious in the form of cracking. But a crack is not a failure, as explained in due course. This article discusses the issues of redistribution through a series of cases. In some, the behaviour is surprising. In others we see that analyses that could never deliver sensible results because they could not represent the behaviour of the structure or even, as we always try to do, represent the behaviour of a more conservative structure.

But first, a word of warning. Redistribution can only help if there is an alternative load path (which is a feature of most structures). It pays to look for the alternative and assess its reliability before condemning a structure.

Determinate structures

Any tall building is, at the lowest level of abstraction, a simple cantilever subject to self-weight and wind loads. Wind can topple an inadequately designed building, and that is true whether it is masonry or a more modern material. It is often thought that strength is not an issue, but if you

Figure 7 Upward view of the retrochoir vaults.

Figure 8 Side slope of the buttress within the roof

keep adding weight, crushing is inevitable and masonry can lay serious traps for the unwary.

If the safety of a masonry structure is governed entirely by stability, the issue of strength does not arise. For millennia, masons have been able to depend on redistribution and very low stresses to ensure that apparently fragile structures defy gravity and entropy. It is never safe to assume that bulky masonry is solid and of uniform quality. Masons knew they could get away with building a solid skin and filling it with what the Romans would have called concrete. Push that too far, though, and the core will cease to provide either support or stabilising ties for the shell and the shell will crush.

Collapses such as those in Figs. 4 and 5 are far from uncommon. Only after the collapse of the civic tower in Pavia in 1989[3] did the sensitivity of rubble-filled masonry to over-stress become clear. If a stress of about half the notional ultimate is sustained for a long time the masonry will slowly crack and disintegrate. Luckily, the dictates of stability mean that it is very rare for masonry to be stressed to these levels in the long term.

'Plastic' behaviour

All structural engineers rely implicitly on the plastic theorems. The underlying 'safe' rule is that a structure will only fall down when it has exhausted all possible ways of standing up. Not all the ways the engineer can think of but all the ways the structure can find. That is pure magic for designers. It is only necessary to find one secure load path to show that the structure is safe. It may crack or deform but it will not fall down.

Unfortunately, this hidden safety factor leads engineers into a very false sense of security in their abilities. To quote Ted Happold again 'design is about achieving the confidence to build'. It is no good having false confidence but in most circumstances, plastic behaviour will see you right. It is necessary to be sure that the load path truly exists. It is always possible, and often all too easy, to construct a conceptual model that does not represent the real structure but just appears to do so.

With existing structures the issue is very different. For masonry, there are all sorts of rules of thumb that are perfectly capable of allowing you to design a safe structure but offer only false confidence when it comes to asking how an existing structure stands up. The underlying message is clear though. If your analysis says the structure is not safe and yet it stands, you have probably missed something. The forces have found a path that you haven't allowed for.

Examples of complex behaviour

Wells Cathedral

Wells Cathedral in Somerset is famous for its inverted arches under the tower, but there are other, to me more interesting, things hidden from public view. Each side of the East window is a flying buttress taking the thrust from t he side wall of the choir. In a photograph from above it looks perfectly normal except that it drops into the roof of the retrochoir (Fig. 6).

In the retrochoir itself, there is no sign of it, just a field of modest vaults and slender columns. The buttress lands on the slender column to the right (Fig. 7). Explore the roof space (Fig. 8) and things are much more interesting. The buttress comes down through the roof and steps sideways. The photograph shows that, while it might be possible to think of this in two dimensions, it certainly won't work that way. So how does it work? One thing about masonry is that because it has thickness and great strength, the force can flow along different lines with no external evidence of different behaviour.

The buttress is inclined sideways from the top, through the roof and down to the vault. This alignment ensures that it leans slightly sideways. If we think of force entering the buttress near the top, accumulating as weight is added and finding its way to the vault fill above the column, all that is required is a slight shear force at the topmost level. The vaults perform two helpful functions as they transfer the load from the base of the buttress onto the slender column: they add vertical load which improves stability, but they also provide a horizontal resistance to remove the shear and torsion effects. So, we can show (with some computation) that the thrust has a path through the structure. But is that enough? Surely strength and stiffness also have a part to play.

Thinking about one joint in the lower part of the buttress, it will be essentially horizontal. The obviously important force is axial but there are also two orthogonal shears and a twist. If we are to show that the buttress is adequate we must at least show that there is a path for all these forces.

A 'zone of thrust'[4] is a band of masonry which is sufficient in itself to satisfy both the stability and strength criteria of safety. It is really only a slight development from the models used by Barlow[5]. In three dimensions, this concept (indeed the whole concept of thrust) becomes much more difficult, but here we have a skeletal structure which exists in three dimensions but is essentially slender in two of them: what Heyman calls a stone skeleton[6]. In this instance, a zone of thrust might sensibly be a circular patch, or even a close representation of the actual shape of the buttress.

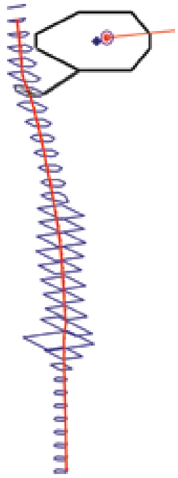


Figure 9 A spreadsheet thrust model of the Wells buttress

Figure 10 Groin stones and Sabouret crack

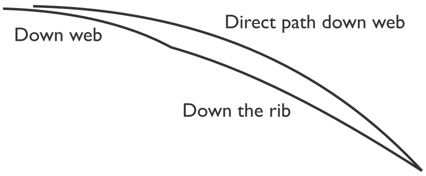


Figure 11 Load path down to the groin then along groin or direct to support

Figure 12 Calva bridge, Workington (viewed from downstream)

Figure 13 Pier loss due to scour

Figure 14 Effect of a dropped pier with hinges at the crown (intrados) and top of backing (extrados)

If we divide the vertical force by the notional material strength we get the area of the patch of material required to support the load. The centroid of this patch needs to be at the centre of thrust. The shear force also requires some strength and that can be provided by an annulus around the initial patch such that the area is sufficient to sustain the shear. Finally, there is a twisting moment or wrench. Another annulus around the first can be calculated such that at limiting shear it will sustain the torsion. The total area is then sufficient to sustain the whole system of forces that must be transmitted. If that patch can be kept inside the perimeter the structure will be safe. In fact, of course, these stresses are not purely additive so a smaller patch would work (Fig. 9).

If this system were modelled in finite elements the conceptual model would probably not convert to a sensible representation of behaviour. In any case there is one more step in the argument. If the thrust comes too close to an edge, the mortar in the joints will deform plastically and the thrust will be forced away, provided that an alternative support can be found to provide the necessary resistance.

This problem was modelled simply in a spreadsheet using only basic geometry and material weights. We can rely on the fact that any necessary rotations would be small and have no detrimental effects. The model can be downloaded from http://billharvey.typepad.com/Wells.xls

Sabouret cracks, vault fill and stability

Sabouret cracks occur in cathedral vaults, not at the wall but some distance into the vault. They are caused by wall spread. The cracks in question are on public view (Fig. 10) but I don't propose to advertise their location here. The structure carries railway loads. It is about 150 years old, but like most such structures it was built in several phases. The most interesting part is a cathedral-like structure, the dimensions of which are best set out in the units in which they were built. There is a long run of cross vaults 30ft wide with a rise of 6ft and an original radius of 21ft 9in. Carpenter's units are feet, quarters and thirds so expect to find 3, 4, 6, 8 and 9 inch divisions but nothing smaller and no others in any of the leading dimensions of arches. Like most arches from the railway era and, indeed, all cathedral vaults, the haunches of these vaults are filled; in this case filled with concrete to the level of the arch crown. The Sabouret crack forms close to the end of this haunch fill, some distance from the main support.

The fill can be viewed in two ways, and I suspect that the masons who built cathedrals saw them differently from modern engineers. In the modern world, the fill is often seen as helping to stiffen the arch and provide a flatter load path from span to span. Indeed a long section of a typical viaduct will reveal that it is very much like a flat thick slab with gentle depressions coupled with deep haunches at the peers. The alternative view is to see it as weight, off the centre of the pier but not far enough into the span to create thrust problems. In this view, the extra weight, offset towards the span, helps the pier to lean into the load.

The long nave is supported by 6ft piers and crossed by 24ft span arches with a radius of 15ft. The corners of the piers are chamfered by 1ft each side. The chamfer is carried to the crossing point with groin stones but the main barrels are of brick. As originally constructed, one side was buttressed by a mere 10ft pier, and when it began to fail the other side followed, producing a lop-sided appearance. The outcome is a very small rotation at the arch springing but the lever action generates a large crack at the crown of the cross vault. The result is an interesting change in behaviour that first requires a view of general stiffness in the vaults.

Many engineers working in the area assume that the force flows down the steepest slope in the vault, then down the rib. Unwrapping that load path shows immediately that it doesn't work. Gathering all the force into one narrow strip of masonry that is a very flat 'arch' is nonsense.

Figure 15 **Calva bridge tilting into the scour hole (reverse direction from Figs 13 and 16)**

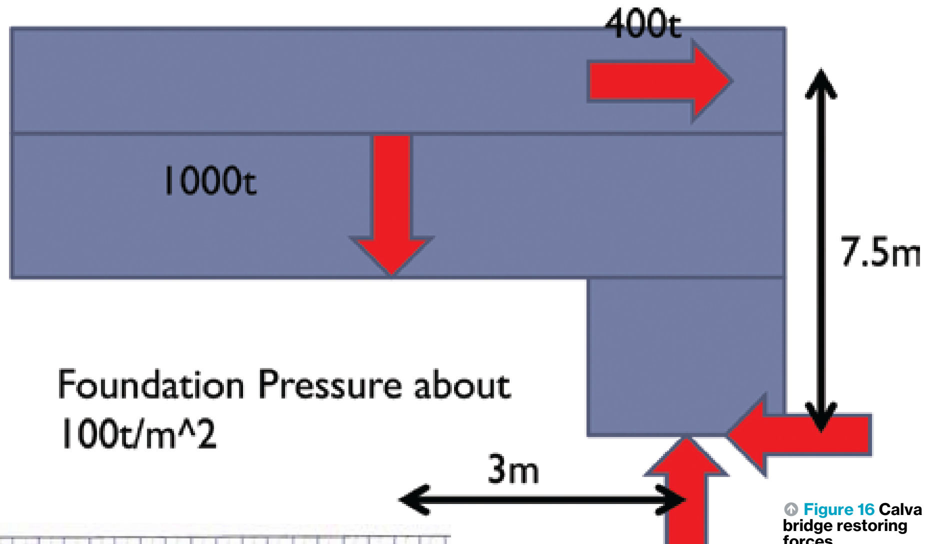


Figure 16 **Calva bridge restoring forces**

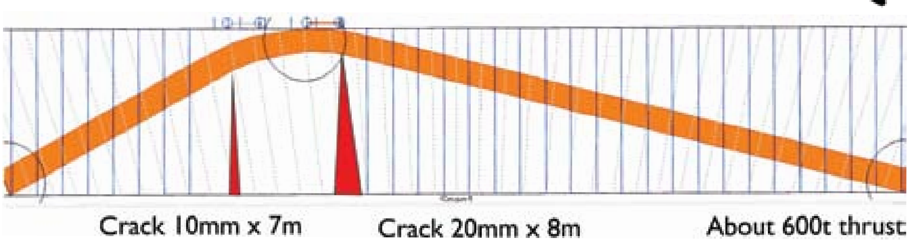


Figure 17 **Calva bridge thrust in plan**

Figure 18 **Calva pier with cracks highlighted**

The natural flow is by the shortest plan route to the support that is also the steepest over all (shown in its simplest form in Fig 11). Only when this breaks down does the load path change and route via the groin, and at that point the stresses can be very high. Of course, church vaults are built as webs on ribs but creep will soon redistribute the force flow.

This 9m square vault is standing at one support on just four bricks, which raises the issue of strength. There are two aspects to this. The bricks are amply strong provided the force is applied uniformly, and that is the great value of a soft mortar. If the masonry begins to crush, the thrust line can flatten which increases the force a little but also increases the supporting area. In many circumstances, masonry can be fail-safe. The pier is now buttressed and unlikely to rotate further.

Calva Bridge

The stone bridge across the River Derwent at Workington (Fig. 12) was built in 1841. It has three spans built to 48ft with a 12ft rise and a three centred shape. Once again this produces interesting geometry with the central radius of 48ft and side radius of 9ft. There are three spans standing on 9ft thick piers. In the floods of November 2009 the south pier suffered severe scour and when the floods subsided the scene in (Fig. 13) was revealed. The bridge has since been repaired and re-opened. Of particular interest to me is how the bridge stood up with such major undermining.

We should perhaps first consider some aspects of articulation of arch viaducts. If an arch pier settles, the spans re-adjust to accommodate it by cracking in the span at the point that creates least resistance. This is best illustrated at Raymouth Road in London where one pier in a long viaduct settled by 100mm. The adjacent arches cracked at the crown and at the top of the backing (Fig. 14). The points at which contact was maintained are at very nearly the same level so that the settlement could be accommodated without generating any increased thrust. The bridge continued to stand (and carry railway loads) for many years before the fault was identified. The point here though, is that spanning over a pier can only support very modest loads and even then only if there is a good deal of horizontal continuity.

At Calva, there was such continuity because it had been filled with concrete some years ago. That is not enough, however, to support the 1000t of stone and concrete over the pier. A study of the final geometry leads to a clear understanding of how that worked. Fig. 15 shows how the pier at Calva tipped and moved sideways. Note the inclined lamppost and the curve in the parapet. But where did the forces go? Indeed, what are the forces?

There is about 1000t of dead load on the pier. The bridge is symmetrical so that weight must be carried on the centre line (Fig. 16). A simple estimate of the centre of pressure says that a third of the width is left and the soil is likely to be behaving plastically so it is reasonable to assume a lever of 3m (1/3 of the 9m width). So there is a couple of 3000tm and that has to be balanced, essentially by a horizontal couple. One side of that couple is shear on the riverbed. If we assume that the other is horizontal arching near the crown level of the arch, those points are about 7.5m apart and the force required is 400t. So where does that come from?

A very simple thrust model of the plan view of the bridge is shown in (Fig. 17}. The horizontal force of 400t is applied as a distributed force across the pier unit. Elsewhere there is no horizontal force so the thrust runs in a straight line. The only available reaction is at the abutments so the slope of the thrust to the right of the force is much less than to the left, and that means the eccentricity is much greater just to the right of the pier block than to the left. Though there are cracks on both sides, that to the left is much smaller (Fig 18).

Figure 19 200mm drop in string course at Rockshaw Road

The Figure also shows how the upper part of the spandrel and parapet are arching over the gap, leading to considerable horizontal cracking both in the walls and in the arch.

This analysis begins with careful inspection and leads into a very simple process. Elastic analysis would have simply shown an overstress, while a discrete element, large displacement analysis might have found the load path but would have been enormously expensive.

Rockshaw Road

Some apparently complex structures have a weak point with no alternative paths. The bridges over the London to Brighton railway line, where they cross a cutting, are typically three semi-circular arches on bank seat abutments and with so-called relieving arches in the piers. Everyone assumes that the pier legs are solid and sound but they are not.

At Rockshaw Road, the local council decided to put in a gully to trap water that was running down the hill into a major road and freezing in the winter. Whoever did the installation was lazy. They put the gully just behind the bridge abutment and knocked a hole in the wing wall to drain the water into the railway cutting. That would have been bad enough, but they didn't compact the fill properly so the gully settled and broke its connection. The water was then being channelled directly into the back of the abutment which settled (apparently slowly) by about 200mm beneath the gully. There is a string course in the brickwork which shows the settlement nicely (Fig. 19). Both the spandrel wall and the arch deformed without significant cracking, but the movement threw extra load on to one leg of the pier that began to crush (Fig. 20).

The problem is essentially very similar to that at Calva but the pierced pier has negligible capacity to resist horizontal shear so the pier leg was subject to additional load that had nowhere else to go. By the time I saw it, the brickwork skin had broken free of the weaker core and was buckling in some places and crushing where it couldn't buckle. The bridge was saved by strapping it up and grouting the pier but it does show that you need to be sure there is an alternative path.

Figure 20 Crushing brickwork. Rockshaw Road rail bridge

Figure 21 A decoration becomes a structure (Inset left: compression induced buckling)

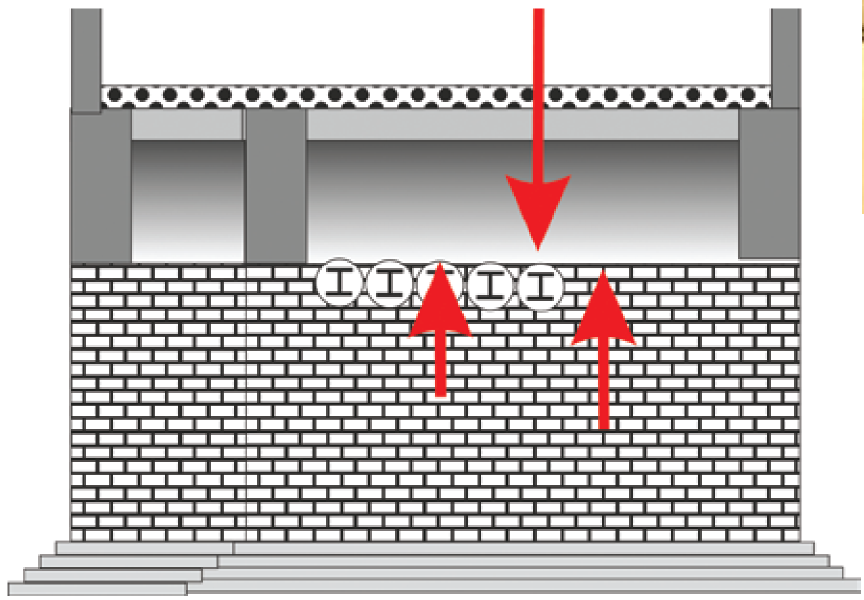
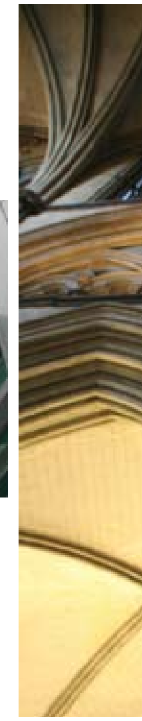


Figure 22 Cross section of pier showing needle positions and construction joint



Bad modelling

There are many examples of wrong-headed modelling. Let's begin with one in a different material. In Beaumont Place behind London's University College Hospital is a bridge between two buildings. It appears to have a trussed support, though that is actually an architectural conceit (Fig. 21). The trouble with such elements is they have some stiffness and therefore attract some load.

The apparently large pin is actually just a plate washer on a thin bolt and the plates creating the joint are thin and have buckled in compression (Fig. 21 inset). In the end, of course, it's a truss. It doesn't need pinned joints because the secondary stresses are negligible. Both the concept of the truss and the detail of the pin are pure decoration.

> "Had we but world enough, and time, This coyness, lady, were no crime"

Viaduct modifications

Construction of a station access under a viaduct required the enlargement of some openings in piers. The design called for the pier to be needled and jacked to relieve the load in the brickwork before it was cut out. The calculations done were complex and yet

Figure 23
Salisbury Cathedral tower pier bend

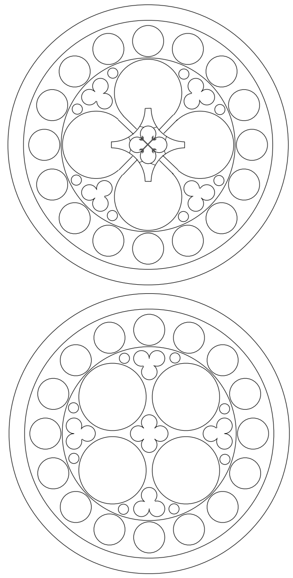


Figure 24
The Dean's Eye tracery. Top: bronze central cross and introduced straight stone. Bottom: with central section rotated 45°

References

1 Thoms, A. H.: 'Repairs to railway viaduct over London Road, Brighton, after damage by enemy action in May 1943'. J. ICE, suppl. To number 8, 24/8, October 1945, pp 353 - 367

2 Walker, D. and Addiss, W.: 'Happold: The confidence to build', Trust Publications, 1997

3 Binda, L., Gatty, G., Mangani, G., Poggi, C. and Sacchi Landriani, G.: 'The collapse of the civic tower of Pavia', Masonry International , 6/1, 1992 pp 11-20

4 Harvey, W.: 'Stability, strength, elasticity and thrustlines in masonry structures', The Structural Engineer, 69/9, May 1991

5 Barlow, W. H.: 'On the existence (practically) of the line of equal horizontal thrust in arches, and the mode of determining it by geometrical construction', Proc ICE, 1846, pp 162-172

6 Heyman, J.: The Stone Skeleton, Cambridge University Press, 1995

managed to ignore some simple aspects of behaviour. In particular, stiff and heavy is not the same as rigid. The viaduct was curved and the curve was produced by putting tapered piers between square arches. The opening was off centre of the structural element, though that was disguised because the viaduct had been widened.

The needle loads were calculated on the basis that the arch above was rigid and so the load in the needles was simply the value of the force in the brickwork below. The trouble with that concept is that the arch is very heavy and stiff but has negligible capacity to transfer vertical load from pier to pier, so what sits on the pier is simply a dead weight. As the masonry block is so stiff transversely it can reasonably be treated as a rigid mass in space. Thus, when the needles were jacked, the arch tilted, relieving stress linearly across the whole width of the pier rather than removing stress locally. The centre of stress left on the pier was a long way from the centroid (Fig. 22). In fact, the section to be removed is nearer to half the width of the original pier (before widening).

This problem can be treated by simple determinate statics. If the uplift from the needles is 0.4 times the total weight and the vertical weight is slightly off centre towards the thicker end of the pier, the remaining force in the masonry will be considerably off centre. The deflection in the needles was nearly 10mm so when the masonry was broken out, the flexure (and therefore the reactions) would probably change little so the situation would be left roughly as intended, though the demolition team would be removing masonry that was still under stress.

A steel frame was then to be inserted in the system and flat jacks used to transfer load in sensible distribution across the span. Unfortunately, the load at the top of the flat jacks would still be applied to the mass of masonry. As the jacks acted, the stiffness of the remaining masonry would be very much higher than that of the needles so instead of transferring load from the needles the uplift on the block would be re-applied.

The stress cycles in the process are relatively simple to compute and may be modest but failure to recognise the pattern and do the calculations must be regarded as careless engineering. Once the error was pointed out, the design team resorted to 3D finite elements to work out the forces and took several weeks over it even though the work was going ahead. The stresses can be computed in less than an hour by hand.

So why The Coy Mistress?

Andrew Marvell wrote a poem entitled: 'To His Coy Mistress' which begins:

Had we but world enough, and time,
This coyness, lady, were no crime

In dealing with existing structures, especially masonry, we have limited resources (not world enough and time). We have to think very hard if we are to get sensible results, or to persuade mistress masonry to let us into her secrets.

If the computer says the structure is inadequate when it is behaving well, the model is probably wrong. That might mean a wrong conceptual model or a wrong interpretation to the computer of the conceptual model.

The habit of assuming big things are rigid is fraught with real danger (look at the tower piers of Salisbury Cathedral, Fig 23). The bending stiffness of structures is much lower than axial stiffness. Foundations can usually be treated as rigid but not so often under masonry.

However, there are knock on effects even when the engineering is sound, if the engineer doesn't look any further than the question posed. The Dean's Eye in Lincoln Cathedral (the rose window in the north transept) is a spectacular piece of mediaeval glass. The tracery was already supported with wrought iron beams and bronze rods but was still deteriorating and had to be replaced. I have no problems with that. Stone weathers. However, a look at the glass says that it doesn't fit and a look at the tracery says it has been blown out before and re-assembled incorrectly. It could never have worked in this form and there are good indications of the real shape both in the glass and in the tracery (Fig 24). Making a spectacular job of rebuilding the window in a broken form is surely neither good engineering nor good conservation. No doubt it will be a hundred years or more before the restoration can be reworked and (if there is anybody left) they can see what the window should really be. ■