Concrete fin-back bridge in USA

A. F. Gee

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■ Mr Gee

Figure 24 provides a starting point for estimating concrete quantities in medium-span prestressed concrete bridges. The straight line should really curve upwards towards spans of 100 m. The Barton Creek number is a handsome margin below the average. A great deal of concrete is in the fins but it is a very cheap concrete, being very thick, almost mass concrete and very easily poured. Therefore, it is actually more economical than one would expect.

83. The same graph for the prestressing (Fig. 25) also shows a significant saving. As the bridge is prestressed in many directions, this result is a tribute to the design.

84. The graph for reinforcement is shown in Fig. 26. Because the bridge was prestressed in several different directions, very little reinforcement was used, particularly in the deck where the deck spans longitudinally; the residual longitudinal compression from the post-tensioning virtually gives enough strength in the deck. There is very little reinforcement in the deck, which is normally where all the reinforcement is in a post-tensioned bridge, and that is what accounts for the remarkable result. Figs 24–26 demonstrate that the design is structurally very efficient.

85. Figure 27 shows the bending moment against span for four lanes with impact and reduction for multiple lane loading. The HS 20–44 is not much more than 50% of HA at 40 m, but it is up to about 80% at 100 m. The significant point is that when the total moment and the dead load are added, using the straight line concrete quantity relationship, the difference in the live loading is not really significant when at about 100 m.

B. P. Pritchard, W. S. Atkins *Transportation Engineering*

Sail bridges can arouse strong aesthetic arguments. Personally, I like their appearance, particularly that of Barton Bridge, although I would also say that I appreciate their technical efficiency more. Nevertheless, I would have better appreciated Barton Creek if the sails had been made symmetrical. No doubt Mr Gee will tell us that the asymmetry matches the skyline, but I feel it would not have been very difficult to add a short span over the road on the high side to make the whole thing symmetrical. It strikes me that it would have looked better and it might also have saved a little money.

87. Mr Gee said that the deck depth savings could be exploited; however, they were not exploited in this case because the bridge was so

high. I think if he had put it nearer the ground and just over the top of the headroom clearances, it would probably not have looked so nice. But deck depth savings can be exploited and this type of bridge is only another form of what is called a sucker bridge.

88. A typical sucker bridge (Fig. 28) is a single span fixed-ended deck slab and varies in depth. The more the depth varies, the more the bending moment is sucked away from the mid-span region until the ultimate—the cantilever—is reached, at which point there is no mid-span moment at all. It has all been sucked towards the support. The advantage offered over a uniform depth bridge is that deck construction depth can be saved over any critical mid-span headroom location. This means that the road profile on the bridge can be lowered, making savings possible in the bridge length besides construction depth.

89. Therefore, the reverse of the above is this sail bridge, which in fact has uniform clearance all the way across between the piers, with the increased construction depth over the piers not intruding into the clearance envelope.

90. Another point concerns the cusp over the piers as found in multi-span sucker bridges or arches, which has some meaning to it because it emphasizes the transfer of the deck load down on to the pier. That is the kind of shape which pleases most people, but the fin does not, because there is a point in the sky which does not seem to be doing anything much except conduct electricity. I feel one could do more with the shape of the sail—perhaps feature the parallel sail construction joints.

91. Another point is that the fin forms the central crash barrier. Were any special measures taken (e.g. special reinforcement at the edges) to allow for heavy impact by big lorries?

92. The costs are, as seems usual for American bridges, staggeringly low: £300–£400 per m² at the current rate of exchange. In the UK it costs nearly £600 per m² to build even slab bridges; stayed girder bridges and segmental bridges cost nearer £1000 per m². How is it that the Americans, with significantly increased labour rates, can build bridges at at least half what it costs in the UK?

D. J. Lee, G. Maunsell & Partners

I am grateful to Mr Gee for putting on record this application of a very characteristic form which I think is expressive of the nature of prestressed concrete. I have been credited with being the inventor of this type of bridge, but do not think that this is quite correct because it is

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Fig. 24

a basic development of a true girder bridge. Even the Forth Bridge is a type of fin-back. So I think it should be thought of in terms of its being a prestressed concrete bridge, and in that sense I think it is characteristic. I think I did coin the term 'fin-back' in print for this type of scheme. I recall that the fin-back whale does have a fin, although it is not very large; also the body of the whale is characteristically striated, and I think this is much more related to the longitudinal prestressing forces. Therefore, I think the term is appropriate. It seems to have been adopted world-wide, even if few are ever built. Barton Creek Bridge seems very appropriate in its location.

Fig. 25

94. To what extent is Barton Creek Bridge load balanced? Is the self-weight alone counter-

ed, and how great a proportion of the live and superimposed load has been allowed for? In other words, is it standing in a no-tension state of a particular element of its loading life? Did Mr Gee allow it to be no-tensile with full loading?

95. With regard to the aerodynamics, is there much of a wind problem? In some wind tunnel tests on another scheme, the fin was found to be interesting. It is rather like a Concorde coming in to land: if one says the launch shedding is stable, then it must be right, otherwise no Concorde would ever land. An aeroplane coming in with such extraordinary wings increases the pressure stability on the underside by up to 40%. It is amazing that to anchor the wind is the vital aspect.

96. The Barton Creek Bridge is a 340 ft (93 m) main span. This is half the span of the schemes for the Kessock and Foyle Bridges. The Orwell Bridge is 190 m, and the Gateway Bridge in Australia, which is the largest box in the world at present by cantilever, is 206 m. I think Barton Creek is just about the right size to demonstrate the delightful nature of this kind of bridge. Could the Author comment on other sizes of span that might be of interest?

K. Sriskandan, Mott MacDonald

I should like to congratulate Mr Gee, not least for winning a commission for a bridge in America. However, I do not like the look of Barton Creek Bridge. It has been described as a fin-back or a sail, but I think it is more of a hump-back. Fig. 23 shows the view the motorist has as he goes across the bridge and I think this shows it in its true perspective. What does the American engineering fraternity think about the appearance of this bridge?

98. A fin running down the middle of a bridge removes all possibility of using the bridge deck in different ways, such as for four lanes in one direction or a contraflow. The structural member in the middle takes away this flexibility. For that reason, I think that any structural member in the middle, whether it be a stay cable or a fin-back, is not desirable.

99. It is surprising that the average thickness of concrete in Barton Creek Bridge was small compared with that in other bridges. Redheugh Bridge, for example, has a span of 160 m and a depth of just under 10 m, whereas Barton Creek Bridge has a depth of 10 m, comprising the fin plus the triangular box. These two are equivalent to two webs each of about 30 cm and therefore the quantities in the two bridges cannot be very different. There is also the complication of the construction of the spines in situ at the same time, and of the transverse and diagonal stressing which is required. I was surprised, therefore, that the costs were lower than for traditional box girder construction.

100. At the present rate of exchange, a cost of \$750 per m^2 would be considered very cheap in the UK. Is this cost typical in America?

101. Is there any significant effect due to lateral temperature differential caused by the sun's shining on one side of the fin?

J. A. Dunster, Independent Engineer

I find the aesthetics of Barton Creek Bridge worrying. I agree that from an engineering point of view it is a very economic design, but aesthetically, perhaps because one is used to arch bridges, it looks wrong. Even as an engineer, it worries me; I prefer the thicker section underneath the bridge rather than over the bridge at the support.

103. To have only three tenders for the actual price is quite different from what would happen in the UK with open tendering. The cost was 20% over the estimate. Were estimates carried out of the conventional cantilever construction at the same time and, if so, were they 20% more?

104. On the question of casting the fin afterwards, what lengths were cast at one time? Did they get longer and longer, or were very long lengths cast in one go? Were there any problems in cracking between the old concrete at the lower part of the fin and the new part?

Fig. 26

B. J. B. Gauld, School of Architecture, Kingston Polytechnic

If Barton Creek Bridge is taken as the prototype of concrete fin-back bridges, what developments are going to take place? D'Arcy Thompson² states that in nature, form follows function. In this case, the structural function is cantilevers and the form should explain that function to the observer. Perhaps the name of these bridges should be changed to 'cantilever fin-back'. The Forth Bridge clearly states the cantilever principle by introducing short simply-supported trusses between the cantilevers. Aesthetically, this bridge introduces the magical number of three which, in esoteric terms, has powerful meanings, as can be found in most religions. If there were only two canti-

Fig. 27 (far left)

Fig. 28 (below). Sucker beam moments

lever towers, the Forth Bridge would look quite mundane.

106. The future development of the cantilever fin-back bridge must therefore include a clearer definition of the cantilever function and experimentation with the number of towers. I think a bridge with three cantilever sections, the central being larger than the others, would look spectacular.

Mr Gee

In reply to *Mr Pritchard*, each sail is symmetrical but one side span is longer than the other, so the bridge is essentially two balanced cantilevers stuck together. The two balanced cantilevers are of different length because of the constraint on the position of the piers. It is environmentally a very sensitive area and there were fairly short limits where the piers had to be located. My office made a drawing of a symmetrical bridge with a short end span, but it looked terrible. Many different plans were tried with the piers as they were, and the eventual solution looked much the best. The architects to the developer endorsed our selection of the five bridges studied and actually expressed a liking for the asymmetry of the fin-back. They said they liked the bridge because it reflected the hills in the background.

108. A sucker bridge is just a variable depth continuous girder. The mid-span depth can be reduced to almost ridiculous proportions if the section is increased sufficiently at the support.

109. The joints on the sail were, in fact, feathered. A v-chamfer of about 40 mm was put in the joints; a bigger one would have led to cover problems.

110. The bottom half of the sail is the standard New Jersey barrier. It has more reinforcement in it than a standard barrier and so by definition is designed to withstand vehicular impact.

111. With regard to costs, some money is saved by not waterproofing and surfacing a bridge, but that is not the whole answer. I have now spent years watching Americans build bridges, and there is nothing exceptional about the cost of this bridge. They do indeed build average standard bridges for \$40 per square foot, however phenomenal this may seem by UK standards. On some jobs, contractors are allowed to get away with things which they would not get away with in the UK, but I do not think their quality is significantly lower. They do a fair amount of finishing and they do paint most of their concrete bridges, although they are not obliged to. They are, however, supremely well organized on site, particularly when aiming to achieve the same sequence of operations on a repetitive basis. One key factor is the flexibility of the labour. Apart from the

specialist trades, they will probably subcontract the steel fixing, and the tendons, ducts, and so on, will be put in by the steel fixer. However, when it comes to the forming and pouring of the concrete, operations such as moving the traveller forward and setting it up ready for the next pour and all the ancillary operations involved in building the bridge, will all be done by the contractors' own men. There is absolutely no demarcation. A man is not a concrete finisher or a carpenter; when he is on the site, he is a workman. This flexibility contributes enormously to the speed with which things can be achieved.

112. *Mr Lee* refers to the limiting span: 100 m is considerably less than the proposals for the Foyle and Kessock Bridges. Were they at the top of the range or is this at the bottom of the range? My feeling is that it is at the bottom. I do not think that a fin-back of much less than 100 m would be economic. It is difficult to know what is the top of the range.

113. Concrete bridges do become heavy, but if one were fortunate enough to have solid bedrock and was not going to spend a fortune on foundations, then I do not see why a fin-back should not be of about 300 m span. For an ordinary continuous variable depth girder or a fin-back, one would have to have very good foundation conditions to make steel economical over about 250 m. At 200–250 m, the continuous girder suffers from a technical problem because the only place the post-tensioning can go in over the support is in the deck. Getting the tendons into the top flange of some long spans (e.g. the Orwell Bridge) is difficult, but getting the concrete in after the tendons is nearly impossible. The fin-back overcomes that problem to a certain extent: the post-tensioning can be spread around a big fin.

114. One or two fin-back proposals or tenders have been unsuccessful for reasons which might be contested, such as aesthetics. Gateway Bridge lost out on price and was beaten by an alternative proposal which used a conventional variable depth continuous girder. The choice was between a relatively simple, albeit enormous scale, single cell box and a four-cell box with ribs and all sorts of things. It was obvious that the former was going to be the cheaper.

115. Designers obviously have different theories as to what is the correct span to depth ratio. A certain moment of resistance can be achieved by making either the section deeper or the bottom flange thicker. Making the bottom flange thicker is less efficient in terms of materials, and therefore it is heavier; this comes back to the problem of foundations, which become very significant for concrete bridges of 500 m spans. If some cubic metres of concrete can be saved by making the bottom flange deeper, and the headroom is available to

make it deeper, it probably pays off. However, purely on superstructure costs, I think it is cheaper to have a thick bottom flange that it is to deepen the section. One may actually use more concrete, but it is cheap concrete: it is a great deal cheaper for concrete in a 6 ft or 8 ft thick bottom flange than it is in a 2 ft thick web, 45 ft deep. My conclusion is that the thick bottom flange is heavy in weight, and the deep section with the thin bottom flange is heavy in appearance and is expensive.

116. I do not like draped sails. This is not a suspension bridge but a post-tensioned beam, and I think that it should flow with the line of the tendons which are basically concave downwards.

117. With regard to load balancing, there are no tensile stresses under full dead and live load because there was a choice under AASHTO. In continuously reinforced in-situ concrete, the permissible tensile stresses under normal dead plus live load are three times the square root of the cylinder strength in pounds per square inch. We opted not to use this; it was going to arise in only a very small area of the bridge because it behaves like a rigid frame and two propped cantilevers. By using a zero tension condition, the reinforcement did not have to be taken through the joints; experience had shown that this would save a great deal of money. The only reinforcement passing continuously through the joints between the segments was in the deck. So in the webs and the bottom flange, the reinforcement is curtailed so that there are no penetrations in the bulkhead. The contractors loved this. Therefore, at the expense of the very slight penalty of an extra continuity tendon in the bottom flange at mid-span—it did not make any difference to the main tendons—we designed for zero tension.

118. No tests on wind effects were carried out, but there have been no adverse reports since the bridge has been completed. The bridge is in a bad location, being across a gorge, and the gorge continues fairly straight upstream and downstream of the bridge. On the bridge on a fairly windy day, one can feel the wind on the windward side, but it is remarkably calm on the leeward side. I think this is because there is a 3 ft high profiled median barrier which the wind hits and is then deflected above head level. There have been no reports of high-sided vehicles suffering traumas or anything like that, so I do not think wind is a problem.

119. The cross-section of the bridge has many advantages. The single triangular box is very simple to form and the ribs are not a great problem. There were no concreting problems with the struts; all the compaction problems experienced were in the webs. I would choose this rib/strut system again. Clearly, there is a relationship with the width: for a wider bridge,

the box will have to be made deeper to get a reasonable angle on the struts. However, having used this cross-section and realized its simplicity and advantages, I would try desperately to use it again and would therefore have to deepen it to suit the width of the bridge. I do not think the span/depth ratio of the box is really critical.

120. In reply to *Mr Sriskandan*, I would suggest that the motorist's view of the bridge as shown in Fig. 23 is not all that unpleasing.

121. The amount of traffic over the bridge is such that Mr Sriskandan's point about contraflow is not a problem. Also, if the surfacing does not have to be repaired, contraflow is not really needed.

122. The 70 m span mark relates to average quantities for an average span. I agree that in a bridge of this sort, the parameter that dictates the quantities is more nearly the maximum span than the average; in fact, they would look spectacular if I moved them to the 104 m mark.

123. To answer *Mr Dunster*, the costs of other alternatives were estimated. The conventional continuous girder and a fin-back were estimated to cost about the same. The estimate was a consultant type of estimate made by measuring quantities and multiplying them by an appropriate rate, but it was weighted by an amount which subjectively we thought would represent the technical difficulty. In the event, the weighting was a little light; so had we designed a conventional girder bridge for this particular site, it might have been cheaper. The most important thing perhaps was that the final price was only a few dollars above the tender price. There were no extras at all.

124. Differential lateral temperature through the fin does not give rise to any stresses, but the fin does deflect. Calculations showed that there was no significant $P-\Delta$ effect. Similarly, the effect of wind loading on the fin is trivial. The vertical reinforcement in the fin is very small.

125. Americans do not waterproof the bridges in the Southern States, and they do not really need to because they never have to use de-icing salts on their roads. The massive deck replacement schemes in America, in which hundreds of square miles of bridge deck have been replaced, have all been in the Northern States. Those bridges were not waterproofed either; they did not have surfacing on them and, moreover, they used very poor concrete. Composite decks had 2000–2500 lb/in² concrete put on them. The replacement bridge decks are not waterproofed either. Better concrete—i.e. 3500–4000 lb/in²—is being used but it is still not good enough in my opinion. Epoxy coated reinforcement is being used and, in some cases, cathodic protection.

126. *Mr Dunster* does not like the aesthetics of the Barton Creek Bridge. The fin-back is not

a cable-stayed bridge and it does not function like a cable-stayed bridge, but in some ways it looks like one—it has the same triangular outlines above the deck.

127. The last length of fin cast was about 300 ft long, 5 ft high and 2 ft 6 in thick. It was cast in one continuous pour and there was no cracking, but it was partially stressed very early. It was stressed for about four hours because one benefit of the concrete problem was that high strengths were reached early on. Segments were stressed in 12 hours; the stress in the fin was very small compared with the stresses around the anchorages in the seg-

ments. The anchorages are in the very constrained apex at the bottom of the fin, the top of the two webs and where the deck comes in; this made it possible to stress at a relatively low strength.

128. As *Mr Gauld* says, three is a magical number and for this reason, four-span bridges are aesthetically unpopular. However, the fin-back may be an exception by focusing attention on the three fins rather than on the four spans.

Reference

2. THOMPSON D. W. *Growth and form*. Cambridge University Press, 1961.