Lessons from history – the steel box girder story

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Synopsis

For many engineers, the steel box girder story starts with disaster. The memories of the tragic events of 1970 and 1971 are still raw for some, and the implications have been far reaching. But the story is also one of bold innovation, lessons learnt and ultimate success. This paper explores the short history of the steel box girder and reflects on how it has shaped the evolution of the popular modern bridge structures we see today.

Acknowledgment

As a student at Bristol University in 1977, I undertook a study into the circumstances surrounding the failure during erection of the steel box girder bridge over the Yarra River in Melbourne. I didn't know then that I would join Flint & Neill upon graduation or that I would eventually be asked to deliver the James Sutherland History Lecture on the subject of steel box girders. Had I known, no doubt I would have paid more attention!

Although I am honoured to be asked to tell this story, I must point out that it is not really mine to tell. It belongs to the truly great engineers in whose footsteps I have had the honour and good fortune to tread. Most of the history I will attempt to relate is relatively recent, and I am acutely aware that some of those great engineers who were directly involved in this ground breaking work, making significant advances in this field, are still alive today. I must therefore beg their forgiveness for any inaccuracy or omission in my account, and ask that they use the discussion that I hope will follow the delivery of this paper to correct my errors.

In particular, I wish to acknowledge the enormous contribution made by my colleagues and former Partners at Flint & Neill, Tony Flint, Brian Smith and John Evans, who have been my mentors and teachers through the years, as well as the many tutors on this subject too numerous to mention at Bristol University and subsequently Imperial College in London. I am also grateful to Holger Svensson and Siegfried Hopf of Leonhardt Andrä und Partner for providing information on some of the post-war developments in Germany which are a significant part of this story.

Introduction

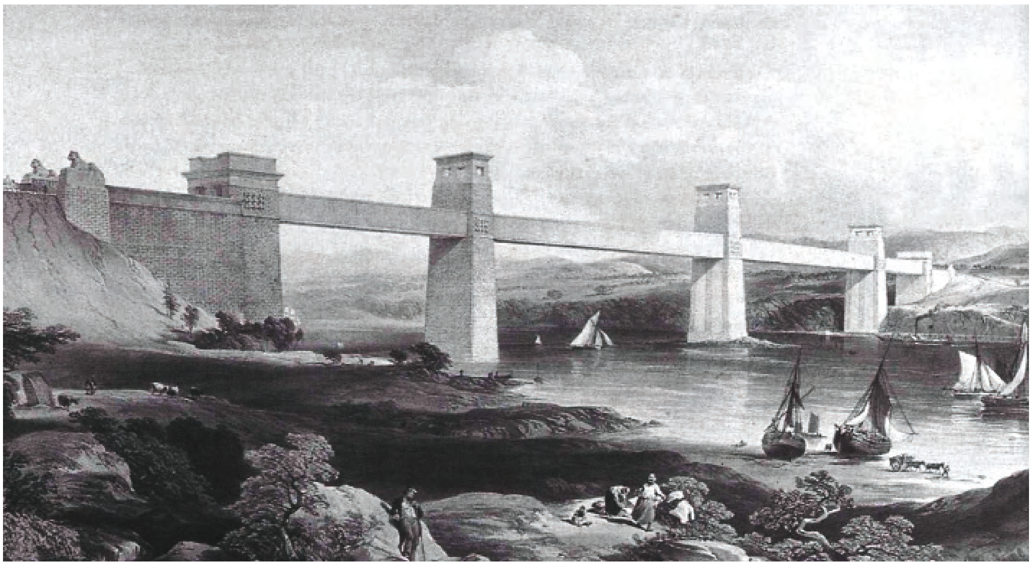
Engineering history is the story of learning from failure. Without failure technology stagnates. It is necessary to try something new from time to time, and then history allows us to judge whether it is a success or not. The best innovations are repeated and improved upon while others tend to fade away. Some early box girder innovations clearly stretched the boundaries a bit too far, but the lessons were learnt and subsequent generations have benefitted as a result.

In the decades immediately after the Second World War, economic circumstances and the drive to build new roads led to the need to find more and more efficient ways of building bridges. In Germany, many new bridges were called for, including several across the Rhine and other large rivers. The story goes that the Luftwaffe engineers, prevented for a while from building new aircraft, applied their skills to the re-construction effort. This would not be the first time that ideas from other industries found application in construction; in this case a familiar lightweight tubular form of fuselage turned into a bridge beam. Whether or not this is the real origin of the modern steel box girder (after all the efficiency of box structures was already well known) there is little doubt that innovative designs for box girder bridges using thin stiffened steel plate began to appear on drawing boards in the late 1940s.

But before we get on to the story of modern steel box girders, it is worth pausing to consider their predecessors.

Early history

The first large bridges to be built as metal box girders were the Conwy Bridge (1849) with a single simply supported span of 125m and the Britannia Bridge over the Menai Strait (1850) in North Wales which was a four span continuous beam of 70 + 142 + 142



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1 Stephenson's Britannia Bridge (*courtesy Institution of Civil Engineers*)

Date	Bridge	Type	Traffic lanes	Main span (m)	Steel box weight	
					(t/m)	(t/m/lane)
1939	Bronx-Whitestone	Plate - suspension	6	701	17	2.8
1948	Cologne-Deutz	Box - Girder		185		
1957	Mackinac	Truss - suspension	4	1158	12.2	3.0
1957	Theodor Heuss	Box – Cable stay		260		
1964	Verrazano Narrows	Truss - suspension	12	1298	39.7	3.3
1964	Forth	Truss - suspension	4	1006	8.0	2.0
1966	Severn	Box - Suspension	4	988	7.1	1.8
1970	Little Belt	Box - Suspension	6	600	12.8	2.1
1971	Erskine	Box - Cable stay	4	305	7.4	1.9
1973	Bosporus 1	Box - Suspension	6	1074	8.2	1.4
1974	Avonmouth	Box - Girder	6	174	8.2	1.4
1975	Cleddau	Box - Girder	4	214	8.4	2.1
1981	Humber	Box - Suspension	4	1410	5.1	1.3
1988	Bosporus 2	Box - Suspension	8	1090	12.8	1.6
1994	Normandy	Box - Cable stay	4	856	10.4	2.6
1998	Great Belt East Bridge	Box - Suspension	4	1624	11.0	2.8
1998	Great Belt Approaches	Box - Girder	4	110	12.0	3.0
2009	Stonecutters	Box - Cable stay	6	1013	29.1	4.9

Table 1 Comparison of steel bridge girder weights (prior to upgrade)


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2 The Cologne-Deutz Bridge (1948)

+ 70m (Fig 1). Both were constructed in wrought iron and both were designed by Robert Stephenson, the son of the steam engine inventor.

These bridges carried steam trains which travelled through the inside of the rectangular box girder which therefore could not have internal transverse diaphragms to stiffen the box walls and maintain its shape. This worked because each box only carried a single rail track so torsion and distortion effects were small. These bridges were a huge breakthrough and a significant innovation. Not only was this the first time wrought iron had been used in a large bridge structure, it was also the first use of a large closed box with thin plate walls. Furthermore, the Britannia boxes were built on dry land and floated out to be lifted into position as complete spans – a technique that is still commonly used today. Sadly, the Britannia box beams were destroyed by fire in 1970. The bridge was reconstructed with arches to support a new steel deck structure which now carries the trains plus a new road on its upper level.

Before the advent of wrought iron in the form of large plates in the mid-19th century, it was not possible to conceive of thin-walled plate or box girder structures, but this material enabled developments in this technology, such as for the oval section arches on Brunel's Royal Albert Bridge in Saltash (1859). By the end of the 19th century, steel plate had become available following the invention of the Bessemer process (1856) and then the Siemens-Martin process (1865), and this enabled the construction of one of the earliest great steel bridges which had hollow box section components – the Forth railway bridge in Scotland (1890).

However, Saltash and Forth cannot really be called box girder bridges, even though their primary structural members are made of large thin walled tubes, and it was not for many years that true box girders began to emerge. Apart from Stephenson's innovative intervention in the mid-19th century, very few metal girder bridges adopted a closed box form, preferring instead to stick with the more familiar truss form of construction. Indeed, it is not until the mid-20th century, 100 years later, that steel box girders begin to come into their own, and this is largely because of the method of joining the plates together.

A new jointing technology and the birth of the modern steel box girder

By far the most common method for joining metal plates together in the late 19th and early 20th century was by riveting. Bolting was also used, but these were not yet of the High Strength Friction Grip type, and bolts in clearance holes sometimes gave rise to difficulties due to joint movements. Rivets were therefore preferred because they provided an effectively rigid joint due to the clamping action achieved as the hot rivet cooled after installation. However, riveting was also very costly, labour intensive, time consuming and hazardous, and a better method of joining plates was needed.

Modern arc welding technology developed during the 1920s and 1930s and after some early difficulties became established as a reliable method for joining steel plates in large constructions by the 1940s. During the Second World War, welding began to be used for building ships, and after the war the Germans turned their hand to the task of bridge reconstruction. In a drive to reduce weight and save material (brought about by acute steel shortages) Professor F. Leonhardt had been experimenting with orthotropic decks and had developed techniques for their analysis. The orthotropic deck was only made practicable by welding, and this enabled weight savings and slender girders previously thought unachievable. Weight savings were also made possible by the development, around this same time, of higher strength steel materials.

Thus the modern slender steel box girder bridge was born, and

Bridge	Date	Girder type	Main span (m)	Span/ Depth	Span/ Width
George Washington*	1931	Truss	1067	120	30
Golden Gate	1937	Truss	1280	168	47
Thousand Islands	1938	Plate	244	125	
Bronx-Whitestone	1939	Plate	701	210	31
Rodenkirchen	1940	Plate	378	115	
Tacoma	1940	Plate	853	350	72
Tacoma replacement	1950	Truss	853	85	47
Mackinac	1957	Truss	1158	100	
Verrazano Narrows	1964	Truss	1298	178	52
Forth	1964	Truss	1006	120	42
Severn	1966	Box	988	309	43
Bosporus 1	1973	Box	1074	358	38
Bosporus 2	1988	Box	1090	363	32

Table 2 Suspension bridge girder slenderness (*Before addition of lower deck)

it is generally considered that the first was the Cologne-Duetz Bridge (1948) designed by Leonhardt[1]. With a main span of 185m, this three span steel box girder replaced an earlier plate girder suspension bridge which had been bombed during the war. The girder had a depth over the piers of 7.8m (span/24) and 3.3m at midspan (span/56), and although it had a stiffened steel top flange, it had a concrete slab added on top as the wearing road surface (Fig 2). Interestingly, the plates were connected by rivetting.

One of the great advantages of the box girder form is that the running deck – the structural element on which vehicles actually travel – is integral with the main girder; i.e. the girder top flange and the running deck are one and the same. Weights and costs reduced because it was no longer necessary to have a separate secondary structure to support the deck independent of the main primary girder. Thus the development of the orthotropic deck plate and the steel box girder went hand in hand. The stiffened orthotropic deck enabled the thin steel plate to carry heavy wheel loads without excessive local bending and distortion. Early versions used open stiffeners (flats, bulb flats and angles), but then closed trough stiffeners emerged to provide improved torsional resistance and lateral distribution of local wheel load effects. The behaviour of the steel deck is closely tied to that of the roadway surfacing material, and developments in orthotropic deck design involved understanding the significance of this interaction (Table 1). However, this was not to be fully investigated until the late 1980s when preparing to re-surface the Severn Crossing, as we shall see.

In post war Britain, without Germany's pressing need for bridge re-construction and with a national economy in crisis, the speed of development was slower. Then in the 1950s, as part of a growing national highway network, plans for long span bridges over the Rivers Tamar, Severn and Forth began to develop. Initially, these were all conceived as suspension bridges (cable stayed bridge concepts having not yet evolved to maturity) with relatively conventional steel truss girders. Indeed the Tamar (1961) and Forth (1964) bridges were constructed this way. Plans for truss girder suspension bridges were also developing elsewhere at this time, such as Mackinac (1957), Verrazano Narrows (1964) and Tagus (1966).

But for Severn Bridge, circumstances conspired to produce a revolution which changed the shape of suspension bridges forever, and opened the door to radical technological developments which continue today. However, to understand the significance of this we must first turn the clock back to 1940 and consider the importance of aerodynamic stability for long spans.

The Tacoma legacy

Any history of steel box girders would not be complete without touching on the collapse of Tacoma Narrows bridge in Washington State[2]. Most engineers will have seen the famous film of the bridge twisting wildly in the wind and ultimately collapsing on 7 November 1940. The failure of 'Galloping Gertie', as the bridge became popularly known, changed the course of long span bridge engineering forever. The bridge had a span of 853m with a 2.4m deep plate girder on each side of an 11.9m wide deck. Crucially, this slender deck had a very low torsional stiffness.

Plate girder suspension bridges, as distinct from trusses, were not new and had first emerged in Germany. Most notable of these, coincidentally, was the original Cologne-Deutz Bridge (1915) which was replaced by the box girder design referred to above. The Tacoma engineer, Leon Moisseiff, was no stranger to suspension bridge design, and many suspension bridges were built in America leading up to 1940, including some with plate girders. Indeed the Bronx-Whitestone Bridge with a plate girder deck had been completed just a year before. Tacoma, however, was very much more slender than its predecessors (Table 2).

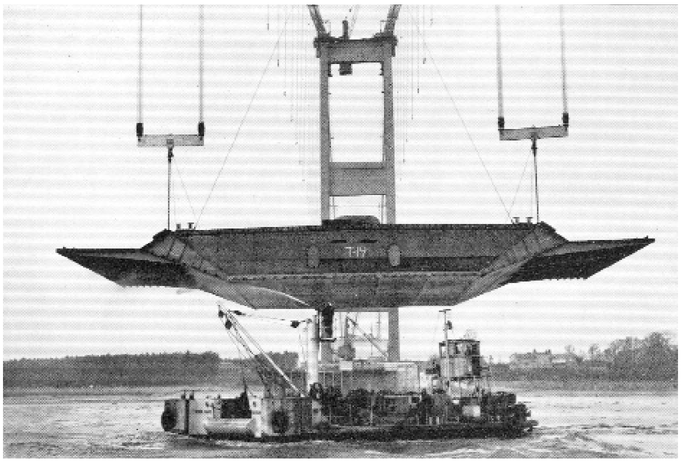
A relatively modest steady wind of about 42mph caused oscillations in the first anti-symmetric torsion mode at about 0.25Hz which built up and eventually brought down the bridge. This spectacular bridge collapse stunned engineers worldwide and exposed a fundamental ignorance of the dynamic effects of wind on bridges. The Carmody Board of Enquiry set up after the disaster included none other than Theodore von Kármán, the famous aerodynamicist who would help to correct this lack of knowledge and go on to establish our modern understanding of vortex shedding and the concept of flutter.

Not surprisingly, the immediate reaction was to freeze plans for other suspension bridges, and those that eventually proceeded did so only after retreating back to using deep, ungainly trusses. The trend towards slenderness and light weight suffered a temporary setback, at least until a better understanding of the new-born subject of bridge aerodynamics was gained.

Which brings us back to England and 1959, where the Severn Bridge designer, Freeman Fox and Partners, was developing a truss girder solution, and wind tunnel tests were already under way at the National Physical Laboratory (NPL) in Thurleigh. Already an innovative, shallower and lighter weight development of the Forth truss, the design was looking promising, but while it was being tested a fortuitous accident occurred: the truss model became detached from its mountings and was destroyed in the wind tunnel. This provided an opportunity for the designers to test an idea they had been toying with for some time. The Freeman Fox team, led by Gilbert Roberts, immediately set about testing a model of a streamlined trapezoidal closed steel box girder, with the assistance of Kit Scruton and Dennis Walshe of NPL. The improved torsional stiffness and streamlined profile of the shallow box girder proved very successful, with significantly improved aerodynamic performance. The box girder design was also very economical, working out about 20% cheaper than the truss, partly due to weight savings and partly as a result of easier fabrication using automatic welding processes. The designers also elected to use inclined hangers to enhance the structural damping and further improve the aerodynamic stability, but that is another story.

The box girder sections were fabricated in Fairfield Mabey's works a few miles away in Chepstow, made watertight with the addition of flotation diaphragms, towed downriver to the site and lifted into place (Fig 3). Starting in late 1964, the girder was erected from the centre outwards and completed 14 months later. It would have been quicker but for bad weather and difficulties with the notoriously strong tides in the Severn estuary.

There is no doubt that the Severn Bridge box girder is among the most important innovations in all 20th century bridge engineering. It paved the way for a whole new era of long span bridges previously thought unachievable. The streamlined box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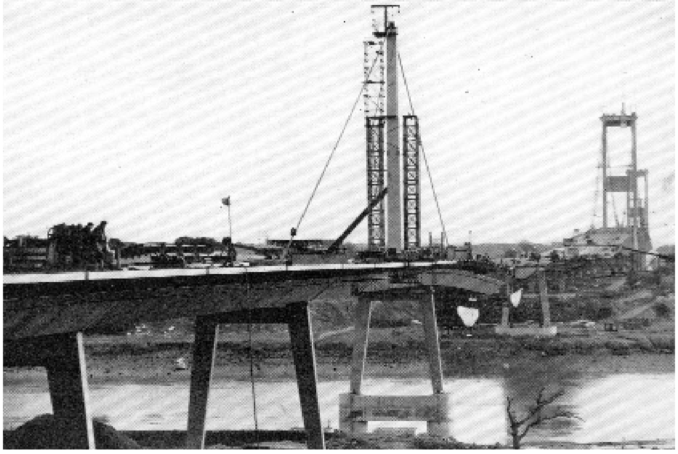
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3 Lifting a Severn Bridge box girder unit
4 Wye Bridge cantilever construction (note the deflection!)

girder is now so familiar to long span bridge engineers that it is hard to imagine a time when it did not exist, but it was only 50 years ago that this form first emerged, and it has come a very long way since then.

Freeman Fox went on to develop its ideas and designed numerous other steel box girder bridges, but there were problems to come and hard lessons to learn along the way. In fact it very nearly ended in tears at the Severn Crossing.

In addition to the famous suspension bridge, the Severn Crossing includes the Wye Bridge, a trapezoidal steel box girder with a cable stayed main span of 235m. Making use of the girder's torsion stiffness the bridge had only a single plane of stays along the centreline – the first of its kind outside Germany. There was only one stay, comprising a bundle of 20 spiral strands, on each side of mid-span, dividing the 235m length into three. Deck erection was by cantilevering over the river using a special under-slung gantry. Individual box units were delivered along the deck until the box containing the stay anchorage steelwork could be attached, whereupon the tower and stays could be installed and stressed to pull up the tip of the cantilever before continuing. The west cantilever went first, with the stay anchor box already in front of the tower and three cable strands already loosely attached. As the box arrived at the tip of the cantilever, a loud bang was heard from the root of the cantilever over the main pier. Some of the deck trough stiffeners in tension had parted company with the pier diaphragm, part of the bottom flange and lower web had buckled, and the bridge was teetering on the verge of collapse (Fig 4). There was no way of pulling the anchor box back, so erection hurriedly continued until a minimum of welding could be completed to the previous box allowing the three strands to be pulled up as far as their capacity would allow. This reduced the loadings at the root of the cantilever sufficiently to permit safe completion of the welding and erection and tensioning of more strands. On the east side the cross-section near the pier was strengthened before continuing with forestay anchor box erection, this time without mishap.

Years later in the 1980s, I led a team doing the structural assessment and design of strengthening for this bridge, and the work included installing a completely new set of cable stays to replace the originals. The plastic deformation caused by that episode was visibly evident, and we devised a process of cable replacement designed to avoid further distress in the affected area. We found that the significance of the wide flange on the behaviour could not have been fully appreciated by the designers, resulting in higher bending stresses than expected and contributing to the incident.

Developments of the genre

Meanwhile, developments had been continuing in Germany, where some of the early cable stayed steel bridges were beginning to emerge. The cable stayed box girder bridge over the railways on Jülicher Strasse in Düsseldorf opened in October 1963[3]. With a main span of 99m and an orthotropic steel deck it is one of the first bridges with stay cables on the centreline, taking advantage of the torsion properties of the steel box.

In the late 1960s it became clear that the British steel bridge design code BS 153[4] was inadequate for the design of box girders. Accordingly, the British Standards Committee drafting a new steel bridge code sought funding for research into the behaviour of plated structures. Sadly this was declined on the grounds that there was sufficient design guidance available from the aircraft industry, even though it dealt mainly with unwelded aluminium components and did not therefore provide an adequate basis for the design of welded steel bridges. We might speculate whether subsequent events might have been different had that research request been granted at that time.

In November 1969, a new steel box girder bridge nearing completion in Vienna across the Danube suffered serious damage due to buckling of the bottom flange. There were several contributory factors, but the unforeseen effects of differential temperature proved particularly significant. The main span of the three-span bridge was built using cantilever construction, and on 6 November the last girder segment was welded into place joining the ends of the two long cantilevers. Accordingly, the mid-span bending moment was zero at this stage. The plan was to lower the main pier supports the following day to induce a mid-span sagging moment and reduce hogging moments over the piers, thereby achieving the intended final dead load bending moment distribution. The sun had been shining strongly that day, warming the top flange and exaggerating the cantilever deflection while the centre piece was welded in. Then as it cooled during the evening the now restrained girder experienced extra tension in the top and compression in the bottom flange due to differential temperature. This was sufficient to cause buckling of the bottom flange in two locations where the stresses would have been low had the supports been lowered as intended. Luckily, the bridge held up and could be repaired *in situ*.

Disaster was narrowly avoided in 1965 and 1969 with the Wye and Danube bridges, but sadly it struck with a vengeance the following year.

Tragedy!

On 2 June 1970, the steel box girder bridge under construction in Milford Haven, South West Wales, collapsed suddenly during construction killing four people (Fig 5). The cause of failure turned out to be an inadequately stiffened diaphragm over one of the piers, exacerbated by excessive eccentricity at the knuckle bearing. The diaphragm buckled during cantilevering of the girder, triggering buckling of the adjacent webs and flanges. The detailing of the stiffener splice joints was also called into question after the

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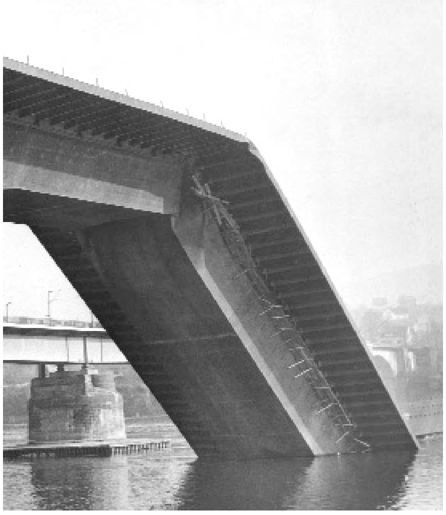

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5 Collapse of the Cleddau Bridge, Milford Haven (1970)
6 Collapse of the Rhine Bridge, near Koblenz (1971)
7 Typical internal web stiffening adjacent to a pier diaphragm (Erskine)

event. This tragedy triggered an in-depth and far-reaching investigation into the design and construction of steel box girders under the auspices of the special committee of inquiry set up under the Chairmanship of Professor (later Sir) Alec Merrison of Bristol University.

Shortly afterwards, on 15 October 1970, one of the western side spans of the West Gate Bridge, a cable stayed steel box girder bridge under construction over the Yarra River in Melbourne, collapsed killing 35. The causes here were complex, and again related to the chosen method of construction. The thin steel deck was designed to act compositely with a concrete deck slab. In service, the composite section would cope with the compression arising from sagging of the span. But during erection, the span was assembled on the ground in two parallel simply supported halves split along the centreline, and lifted without the concrete deck. In this condition the thin steel deck plate was unrestrained and buckling occurred along the free edges on the centreline. The problem would have been evident as soon as the half-girders were lifted, but rather than put them back on the ground to deal with the problem, the lift went ahead with a view to sorting it out in the air. An ill-fated decision was made to remove some bolts and use kentledge in an attempt to straighten the plates and fit the two halves together. This error precipitated the collapse, but in many ways the greater fault lay in the lack of adequate supervision and in the poor communication and support provided by the designers. A poor industrial relations climate with the construction unions also contributed.

As if that wasn't enough, on 10 November 1971 the steel box girder bridge under construction across the Rhine at Koblenz collapsed, killing 13 (Fig 6). Again this involved cantilever construction where temporary bending moments exceeded girder capacity at a position where stresses would be low in the finished bridge. The failure occurred at a box splice joint position, aggravated by poor detailing of the longitudinal stiffener splices to accommodate the erector's chosen welding machine.

Suddenly, with three fatal steel box girder collapses in just 18 months, there were all sorts of questions being asked about this form of construction and an urgent need for some answers.

New recommendations and new design and workmanship rules

Less than a year after the Cleddau collapse, the Merrison Committee produced an interim report in May 1971 with new design and workmanship guidance rules[5]. The Committee oversaw an extraordinary amount of research and development work leading ultimately to the publication of the *Interim Design and Workmanship Rules* (IDWR) in 1973[6]. Meanwhile, the Royal Commission of Inquiry set up in the wake of the West Gate disaster completed their investigations in Australia[7] and additional research was carried out to support the re-design and re-construction there[8]. The reports of the Merrison Committee and the Royal Commission of Inquiry should be essential reading for all engineers, particularly those wishing to engage in bridge design and construction.

It is hard to over-state the significance of the enormous body of work that was carried out in great haste during the early 1970s. The research focussed on gaining proper understanding of box girder and thin steel plate behaviour and the production of new design and workmanship rules, and it remains one of the most intense and significant periods of engineering research in recent history.

In addition to the IDWR, the Merrison Committee also produced recommendations for the following essential control measures:

- A fully independent design check for large or complex bridges
- Independent check of the contractor's temporary works and proposed erection method
- Supervision of construction by the designer.

These were immediately adopted for all major bridges in the UK and elsewhere. Unfortunately, these requirements are now sometimes relaxed in order to cut costs, particularly where bridges are procured through private sector initiatives and design and construct contracts, and the hard-learnt lessons of the past are in danger of being forgotten[9].

The IDWR adopted the limit state method of design for safety

Date	Bridge	Deck plate		Trough		Trough to deck weld	Surfacing thickness
		width	t (mm)	depth	t (mm)		
1966	Severn	305	12.7	225	6.4	Fillet	38
1971	Erskine	305	12.7	225	6.4	Fillet	38
1973	Bosporus 1	318	12.7	255	6.4	Fillet	38
1975	Cleddau	305	12.7	285	6.4	Fillet	38
1978	West Gate	305	12.7-19	203	6.4-7.9	75% part pen	50
1981	Humber	286	12.7	260	6.4	Fillet	40
1988	Bosporus 2	327	14	274	8	Part Pen.	38
1997	Tsing Ma	300	13	250	8	80% part pen.	40
1998	Great Belt East Bridge	300	12	300	6	83% part pen.	55
2003	Carquinez	360	16	305	8	7mm part Pen.	38
2009	Stonecutters	300	18	320	9	Part Pen.	

Table 3 Examples of steel orthotropic bridge decks with closed trapezoidal trough stiffeners

and serviceability, which had first been proposed in the late 1960s by the British Standards Committee B/116. There was some controversy in the 1970s and early 1980s as engineers all over the world were forced to abandon the old familiar working stress approach and adapt to the new limit state philosophy, but eventually limit state won the day.

As a consequence of these events, the UK Department of Transport instigated a substantial programme of strengthening to steel box girder bridges in the mid-1970s known as Merrison Strengthening. Bridges already built or under construction were strengthened and new bridges re-designed to ensure compliance with the new Merrison rules. The components most affected tended to be thin web, diaphragm and flange plates and their associated stiffeners, which were reinforced by the addition of extra stiffening or doubling plates to reduce slenderness and increase critical buckling stresses (Fig 7). Load bearing diaphragms were reinforced over bearings and at web boundaries where shear stresses were high, and intermediate diaphragms were also strengthened. Deficiencies in primary shear capacity of webs close to supports were a common finding. Bulb flat stiffeners, manufactured initially for welded ship hulls and then widely adopted in box bridge decks, also needed attention.

The collapsed bridges were re-built, this time without mishap, others were strengthened and given the all-clear, and thanks to the efforts of the engineers, the lessons learnt from the research and the design and workmanship rules, steel box girders slowly began to return to favour as economic and elegant engineering solutions, particularly for long spans.

The IDWR applies directly to the assessment and design of these structures. The rules specifically allow, for example, the determination of the effects of geometric imperfections and residual welding stresses on the behaviour of stiffened plates. They also explicitly address the behaviour of multiply stiffened panels prone to complex buckling modes. However, they demand a certain degree of expertise and specialist knowledge in their interpretation and are relatively time consuming to apply. They are also unnecessarily cumbersome for the design of many simpler steel structures. Eventually, a simpler design standard was called for. In his Gold Medal Address to this Institution in 1989[10], Dr A. R. Flint, a key member of the Merrison Committee, reflected that in the race to find solutions there was no time to be brief in the code drafting. This required more time, and it wasn't until 1982 that the new steel bridge code BS 5400 parts 3 and 6[11] finally emerged to replace the now obsolete BS 153[4].

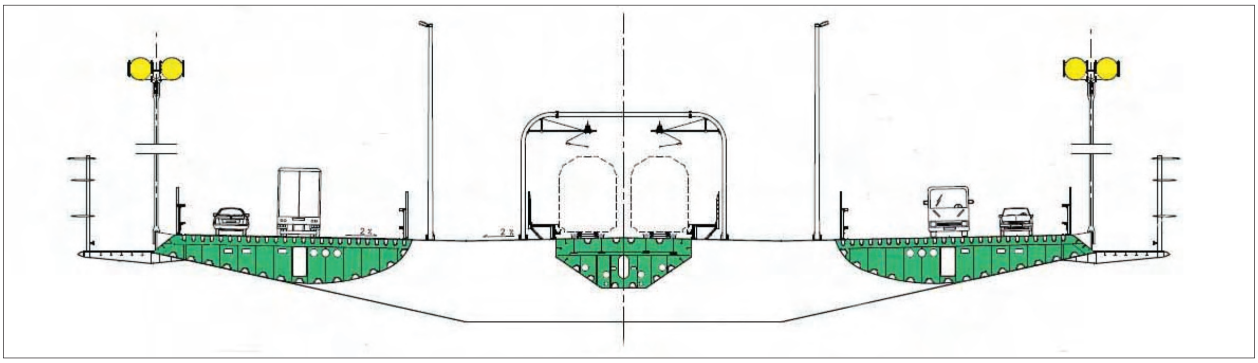
The new code simplified the engineer's task by building in certain conservative assumptions and removing the requirement to explicitly determine aspects such as residual stresses and imperfections in the design of new bridges. Certain undesirable modes of behaviour (for example lateral torsional buckling of open stiffeners) were effectively ruled out by imposing conservative shape limitations for stiffeners and plates. The behaviour of a stiffened compression flange, for example, could be reduced to the consideration of a single stiffener with an effective width of flange plate acting together as a pin-ended strut. BS 5400 was simpler to apply than the IDWR, and the added conservatism had little effect on the cost of new bridges since the penalty for selecting slightly stockier stiffener sections was low. However, this conservatism was to become a problem when applied in the assessment of the existing bridge stock in the 1980s, as we shall see.

Strengthening and upgrading

During the 1980s, recognising that increases in goods vehicle weights and numbers were leading to bridges carrying well in excess of their design loading, the UK Government instigated a widespread bridge assessment programme. One of the earliest structures to be addressed was the old Severn Crossing. The steel box girder structures carried the M4 motorway between England and Wales but were designed in the late 1950s long before the M4 motorway was built. They had already been strengthened in the mid-1970s under Merrison, and were now in need of strengthening again. It was immediately clear that straightforward application of the design code[11] would be hopelessly over-conservative and lead to a lot of unnecessary strengthening if applied in the assessment. Consequently, a set of bridge-specific assessment criteria was devised, incorporating the more appropriate and explicitly relevant IDWR requirements. The resulting strengthening and upgrade works, carried out while the bridge continued to carry traffic, broke new ground, won awards, and set the scene for what was to follow for other steel box girder bridges[12].

A similar approach was taken in strengthening the Erskine and Cleddau bridges, using the IDWR and adopting a bridge-specific assessment approach to achieve substantial savings compared to what would have been required by a straightforward application of BS 5400. We are currently engaged in the similar but even more challenging task of upgrading West Gate Bridge to carry 10 lanes instead of eight[13].

Among other things, the Severn Crossing work focussed attention on the problem of fatigue in steel orthotropic decks. We now know that good detailing and workmanship, particularly in trough-to-deck and trough-to-crossbeam welds is vital for long fatigue life, but this was not always so well understood. The need for deck resurfacing also led to research at TRL, Bristol University



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8 **Proposed Messina triple box girder section - note curved soffits**

9 **The twin box of Stonecutters Bridge (2009) (*photo: Courtesy Arup*)**

and elsewhere to study the behaviour of the surfacing material and underlying deck plate. Considerable effort was applied to determine optimum solutions for the repairs at Severn[14], and a large body of work has subsequently been done in this field by many practitioners all over the world as the steel box girder has gained in popularity. Orthotropic deck details have evolved partly through empirical means and partly through the application of modern finite element methods unavailable to earlier practitioners (Table 3).

Corrosion protection systems have also developed. Some early boxes were unwisely coated internally with red lead paint, unwittingly presenting later difficulties for those engaged in strengthening works because of health and safety concerns over paint removal. The technique of dehumidification to eliminate internal painting, pioneered for Little Belt Bridge, is now widespread. System running costs are not high, and the potential savings from not having to paint the internal surfaces can be considerable.

Modern developments

Recent strengthening and upgrading programmes have taught several lessons, such as the importance of providing easy access for inspection and maintenance; something apparently not considered by early designers. Also, some standard detailing rules (e.g. simple maximum bolt spacing) can be adapted when reinforcing internal stiffeners. We have developed splints to prevent stiffener buckling, for example, which do the job but do not comply strictly with rules.

Modern fabrication systems enable even more economic manufacture of large stiffened plates, including trough-stiffened orthotropic deck panels, automatically compensating for the complex shrinkage and distortion effects. Such systems also make curved soffits possible giving a more streamlined profile and better shell strength. The super-long Messina bridge (3300m main span) has such a curved soffit and a multi-box design for superior aerodynamic performance (Fig 8).

European engineers are now coming to terms with the new Eurocodes, and everyone is rightly concerned about sustainable design, where recyclable steel materials generally score well. These may bring about some subtle changes for future developments, but one is for certain; the steel box girder has well and truly come of age!

Conclusion

Steel box girders have had a relatively short and turbulent history, but engineers now have the tools to design these structures with confidence. It was not always so, and credit is due to those who developed and refined the early ideas.

Important lessons, learnt the hard way, may be in danger of being forgotten as modern economic and commercial factors bring other pressures to bear on designers. Steel box girders have a strong future, and still provide innovative solutions such as the twin box for Stonecutters Bridge (Fig 9), but in the rush for progress it is vital that we do not forget the lessons of the past.

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