West Gate Bridge collapse – the story of the box girders

Sean Brady relates the failure of several box-girder bridges of the 1960s and 1970s and explains how these led to new design rules and workmanship guidance.

Introduction

On 6 November 1969 in Vienna, Austria, three loud bangs punctuate the evening air. The bangs originate from the banks of the River Danube where the construction of the Fourth Danube Bridge is under way. The 412m long continuous box-girder bridge hasn't collapsed, but it is hanging in the air, kinked and distorted[1].

Seven months later and almost 2000km away, one of the longest bridges in Europe is under construction near the seaport of Milford Haven in Wales[1]. It too is a continuous box-girder bridge with seven spans. The free cantilevering erection method has been adopted for its construction. On 2 June 1970 one of its cantilevered spans is stretching 61m over the River Cleddau when it suddenly buckles over a support and collapses. There are four fatalities.

Fast-forward to 10 November 1971, and we find ourselves in West Germany, where a continuous box-girder bridge over the River Rhine is under construction. It's the first all-welded bridge in West Germany, it has a central span of 236m, and it too is being constructed using the free cantilevering erection method. Then its bottom chord suffers a compression failure and the bridge buckles – not over the support, but halfway along the cantilevered span. It hangs like a broken-necked animal – its head in the river[1]. This time there are 13 fatalities.

Then, on 9 November 1989, the Berlin Wall comes down. Over time the East German files yield another continuous box-girder collapse that had been kept secret. Back in 1973, a bridge failed in Zeulenroda, about 100km from Leipzig[1]. Four died, but because it happened on the 12th anniversary of the building of the Berlin Wall, it was hidden from the public and the wider world.

Among these box-girder failures, there was one more collapse. It was the most catastrophic and claimed the greatest loss of life throughout these troubled years in the box-girder bridge's evolution. It would remind us that our greatest lessons are those learned from failure, and that sometimes these lessons are hard won. We go then to Melbourne, Australia, where our profession paid the highest price for the belief that we understood the subtleties of steel box-girder construction.

West Gate Bridge

The West Gate Bridge planned for Melbourne was eight lanes wide and 2.6km long. It would consist of 67m long concrete approach spans, and five continuous steel box-girder spans totalling 848m. The box-girder spans would have trapezoidal sections consisting of three cells, and they would be supported by cables as they stretched out over the Lower Yarra River[2].

The design was carried out by UK consulting firm Freeman, Fox & Partners – the same consultants that were working on the Milford Haven Bridge in the UK. At this stage, when construction on West Gate began in April 1968, the first of the significant box-girder collapses over the River Danube was yet to take place.

From the onset there were challenges: there were widespread labour strikes and the steel contractor had to be replaced in 1970. Then, along came news of the Milford Haven failure. Freeman, Fox & Partners claimed its collapse was a once-in-a-lifetime occurrence, but still undertook strengthening works on West Gate. They also pointed out that a different construction methodology was being used in Melbourne: the bridge wasn't being built by the free cantilevering erection method, but the actual methodology it was being built with would prove fatal.

The contractor was fabricating half of each span on the ground – imagine cutting each span along its length, leaving two half-width spans. Each of these half-spans was then, in turn, lifted 50m up in the air and slid into position (Figure 1). In this way, the contractor halved the load for each lift – albeit doubling the number of lifts. By the time of the Milford Haven collapse, the east and west spans of the West Gate Bridge, each 112m long, were ready for erection.

Then, one of the half-spans on the east side developed a problem. It was fabricated, but when it was lifted off its temporary trestles at ground level, it suddenly developed a buckle on the top free flange – the flange that would run down the centreline of the bridge when it would be connected to the other half-span.

The buckle occurred because of the decision to lift each half-span separately. While the free flange was stiffened longitudinally and transversally, there was a problem with both sets of stiffeners (Figure 2). The transverse stiffeners didn't have the necessary stiffness to restrain the longitudinal stiffeners, and this lack of restraint resulted in the longitudinal

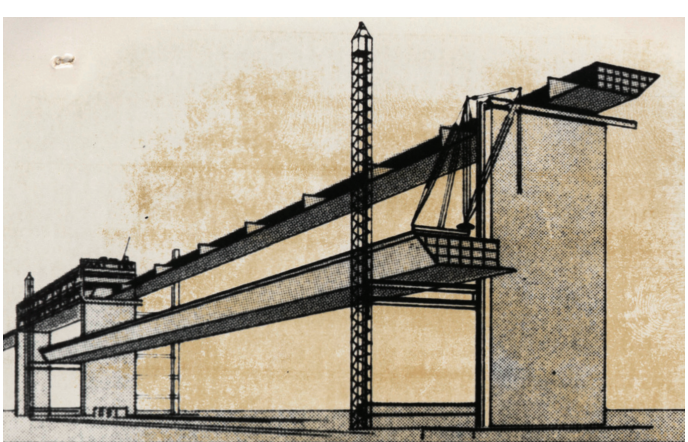

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Figure 1 Diagram showing half-span being lifted into position

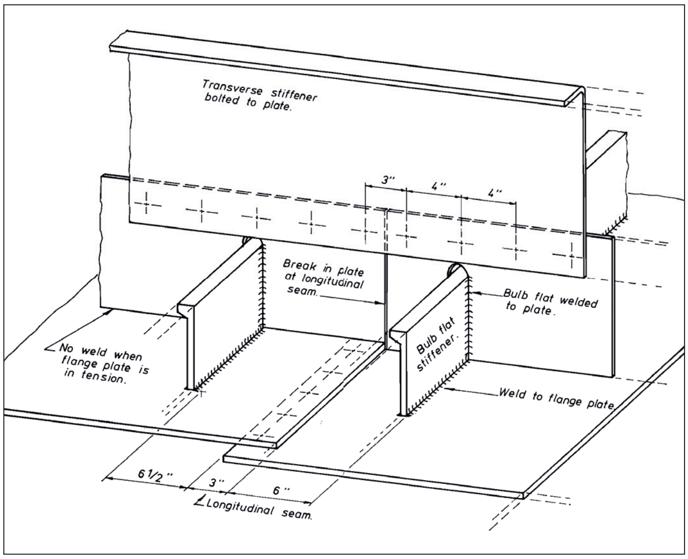

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Figure 2 Detail of stiffeners to plating[2]

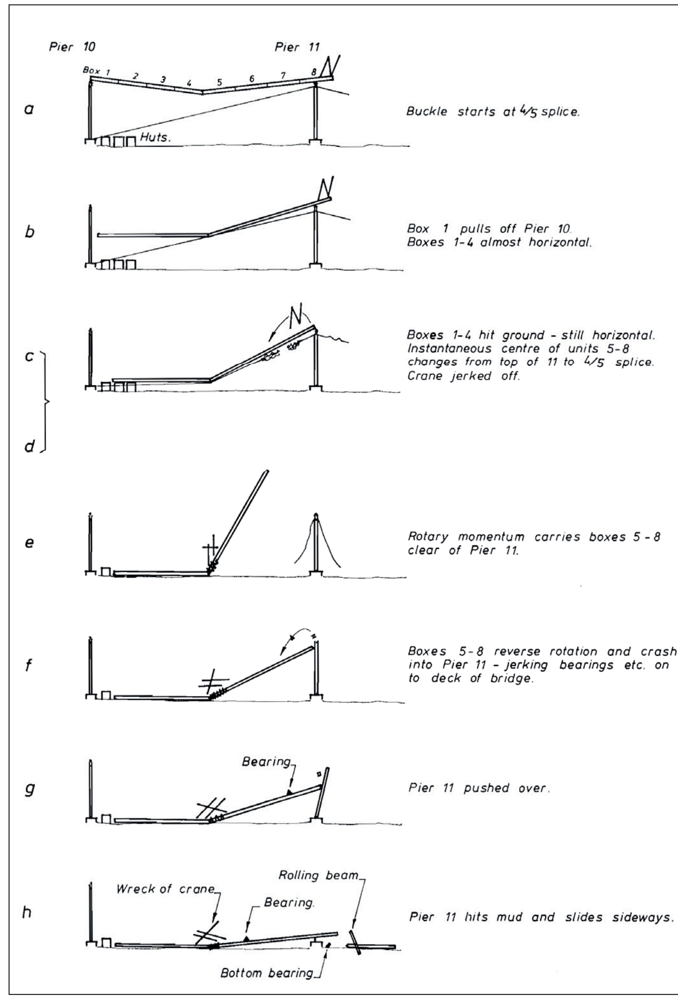

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Figure 3 Dynamics of failure[2]

stiffeners having a longer effective length (and therefore a lower buckling load) than anticipated. Further, the longitudinal stiffeners had joints every 16m. These joints consisted of a flat splice plate bolted to each stiffener, but this plate had a smaller cross-sectional area than the longitudinal stiffeners and it bridged a gap of 318mm between the points where one stiffener ended and the other began. In addition, the plate was offset from the stiffeners, and this eccentricity, in combination with a smaller splice plate area and the gap between the stiffeners, created a point of weakness at every joint in the longitudinal stiffeners.

So, there was now a buckle in the flange plate, but rather than lowering the span back onto its trestles and removing the buckle while it was still at ground level, the decision was made to continue with the lift and somehow attempt to remove the buckle when the span was in its final position – at a height of 50m. But this buckle was significant – 380mm – and once the span was placed in position, there was no way it could be unloaded. Despite this, the lift went ahead.

Now they had to straighten the buckle in the air, and the method chosen was to remove bolts from some of the transverse splices in the top flange – essentially removing the top flange's ability to carry compression stresses locally. Then, with the stress thus relieved, they could let the two flange plates slide over one another and flatten out the buckle. Once flattened, new holes were drilled or existing holes were widened in the overlapping plates, and new bolts installed.

WESTGATE BRIDGE © PUBLIC RECORD OFFICE VICTORIA

Figure 4 Workers inspect bridge after collapse

Attention turned to the west span. In order to prevent buckling of the free flange of these half-spans, they stiffened the flange itself with an extra longitudinal stiffener, and they also added cross beams running diagonally from the top free flange back to the bottom flange. This arrangement worked and buckling was prevented during the lifts. But when they went to connect the two spans, they discovered that there was a vertical gap of 115mm between them.

While they had faced this sort of issue on the east span, they had been able to remove it with hydraulic jacks. But the gap of 115mm on the west span was too large a distance for the jacks to close, so they placed 51t of large concrete blocks on one half-span to close the gap. It worked, and the two halves were brought into line. But suddenly, the entire upper flange buckled across its width – the one thing they'd been trying to prevent had occurred. While there had been sufficient capacity to prevent buckling during the lift, the extra loading from the concrete blocks was too much.

The assembly of the span sat dormant for one month until it was decided to use the same method to relieve the buckle as they used on the east span – they would remove bolts from the transverse splice, relieve the stress, and straighten the buckle. But there was a significant difference between the west span and east span – the west span had additional loading from the concrete blocks and the buckle was considerably larger than that of the east span.

They began removing bolts. The stresses in the remaining part of the top flange began to increase – with every bolt removal the neutral axis was being lowered and there was a loss of cross-sectional area in the section. They removed 16 bolts. Then kept going. When 37 bolts were removed, the bridge had had enough: its net section failed and the remaining bolts in the top flange sheared. The span became a mechanism (Figure 3). The left-hand half-span began to drop downwards. The load then shifted to the right-hand half-span because it was partially connected. Then the entire span collapsed 50m to the ground below (Figures 4 and 5). There were 35 fatalities.

Learning the lessons

Steel box-girder bridges gained popularity in post-war Europe, particularly in West Germany where they needed to replace the bridges destroyed in World War II. Rumours suggest that the steel box-girder concept was driven by Luftwaffe engineers who were prevented from building new aircraft, so they turned their skills to bridge building. Also at play was the move away from suspension bridges in the wake of the Tacoma Narrows Bridge collapse[3]. The images of "Galloping Gertie" twisting in the wind and tearing itself apart left a nervousness in the profession that wasn't easily shaken off.

The events from 1969 to 1973 were an almost unprecedented series of bridge failures – five bridges and 56 fatalities. The rapid collapse of the bridges was stark: the Fourth Danube Bridge in November 1969, followed by Milford Haven seven months later, followed by West Gate Bridge four months later, followed by the Rhine River Bridge 13 months later, and the Zeulenroda Bridge 21 months later. Such a rapid series of events illustrates how difficult it was to undertake comprehensive investigations and disseminate information back into the profession to arrest the flow of failures. Even though some strengthening of West Gate had occurred in the wake of Milford Haven, it wasn't enough to address an

Figure 5
Bridge span after collapse

endemic lack of understanding about bridges built from thin plates.

The three-span, continuous Fourth Danube Bridge collapsed largely because of temperature effects. During its construction, both sides of the centre span cantilevered towards one another. On the afternoon of 6 November 1969, the two cantilevers met in the middle and were joined. But the warm temperatures during the afternoon had caused the spans to deflect more and they had to be shortened by 15mm at the top. Then in the evening, the temperature dropped, which placed the top flange in tension. As the temperature drop continued, tension in the top flange increased, which then placed the entire bottom flange in compression. (The original plan was to lower the two inner supports once the cantilevers had been joined, which would have prevented this behaviour, but it had been decided to undertake this lowering the following day.) The compression in the lower flange, along with the use of flat bar stiffeners, caused the bridge to buckle in three places – thus resulting in the three loud bangs heard by Vienna residents.

The Milford Haven collapse was initiated by an inadequately stiffened diaphragm – the designers at the time were unaware of the complex behaviour of diaphragm plates, and the design codes reflected this lack of knowledge. The West Gate collapse – as we know – was the result of a variety of causes, but central was a lack of understanding of the behaviour of stiffening plates.

The Rhine Bridge collapse was caused by the buckling of its compression flange, not over the support, but halfway along the cantilever. (There were a number of reasons why the buckle occurred at this unusual location, one of which was that this was the anticipated location in the finished bridge of zero moment, and it is assumed that the stiffeners were minimised at this location.) Also in play was an issue that echoes West Gate – the buckle occurred where the longitudinal stiffeners were spliced. Finally, the Zeulenroda Bridge collapse appears to have been caused by insufficient flange plates and longitudinal stiffeners – but this failure is short on specific details.

There followed a flurry of activity after the four known failures. In Australia, there was a Royal Commission into the West Gate Bridge failure; and, following the collapse of the bridge at Milford Haven, the Merrison Committee produced an interim report with new design rules and workmanship guidance. This research was put into practice by the industry and existing bridges were strengthened.

Failure will always be part of human endeavour – primarily because we humans are involved in it. Structural engineering – just like all professions – can never truly advance without its failures. This is a sad reality of our profession – we don't get a chance to build prototypes and iron out the bugs. The testing of assumptions and design methodologies happens in the real world, in public view, and sometimes with tragic consequences.

Ensuring that the lessons are learned from these tragedies, as they were with the box-girder bridges, will never bring back the people who died or take away the pain that they left behind, but it may just stop it happening to someone else.

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