

# New Civil Engineer

## Fracture surgery | Forth Road bridge repairs

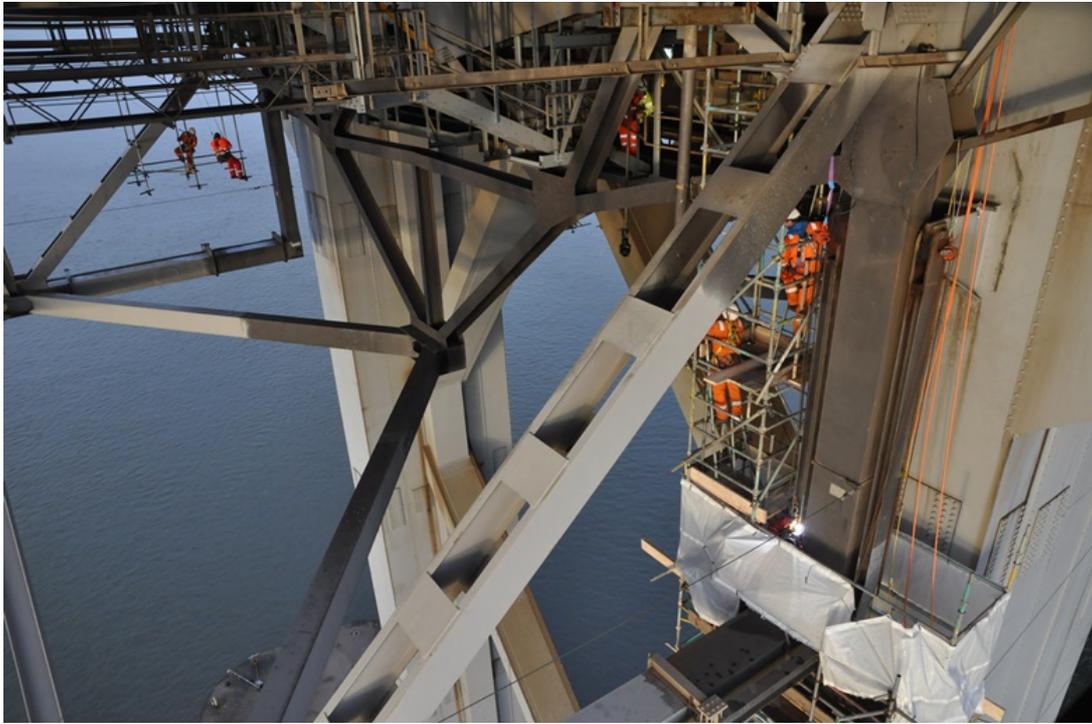
7 November, 2016 By [Katherine Smale](#)



On 3 December 2015 the Forth Road Bridge, one of the main arterial routes into Edinburgh, was closed. A 35km diversion was put in place and the media descended.

The problem? One of the truss end links – a critical structural element that supports the suspension bridge's road deck – had fractured.

The truss end links are situated in eight locations on each side of the two towers. Each one is located under the deck and is an assembly of two vertical, parallel, 5m long steel H sections, sandwiching the truss end posts. They connect to the bridge tower via 1.2m long brackets at their top and to the bottom chord of the truss at their base.



Forthbridge(2) scaffolding and inspection

Worker inspect the truss end link from suspended scaffolding

Both connections are pinned, effectively cradling the truss, transferring vertical forces back to the tower and theoretically allowing the truss to swing freely back and forth with the movement of the deck.

The decision to close the bridge was not taken lightly. In the Scottish Parliament it was described as an event of national significance.

Had the truss end link failed completely, it was calculated that the bridge would not have collapsed, but that the deck would have dropped about 150mm under a dead load. Under a traffic load, it would have dropped 500mm to 600mm – enough to create serious problems for motorists. The client, Transport Scotland, was left with no other option but to shut the bridge.



Forth road location

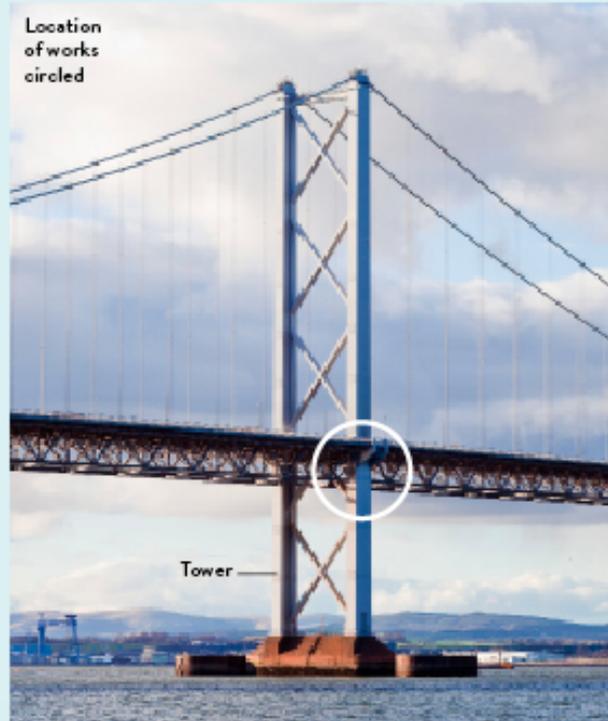
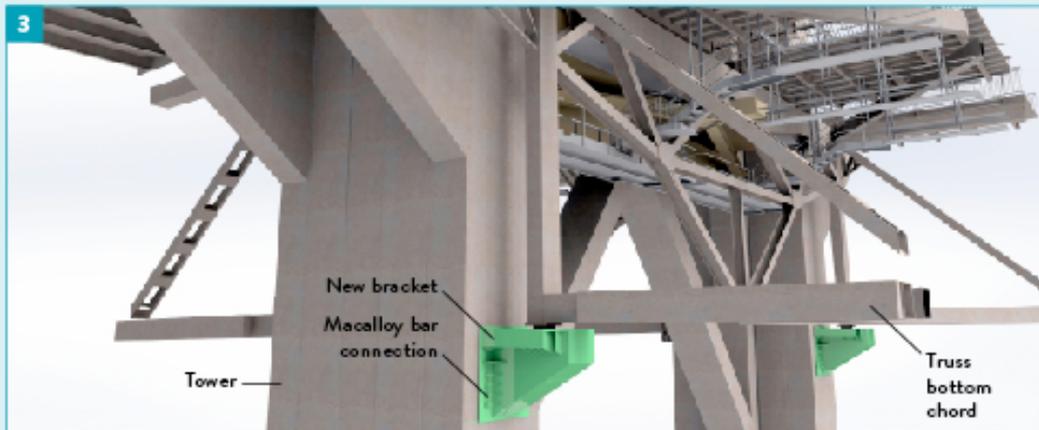
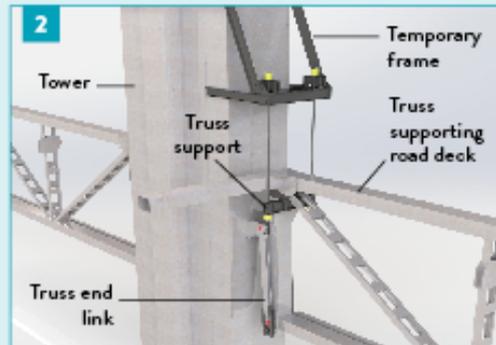
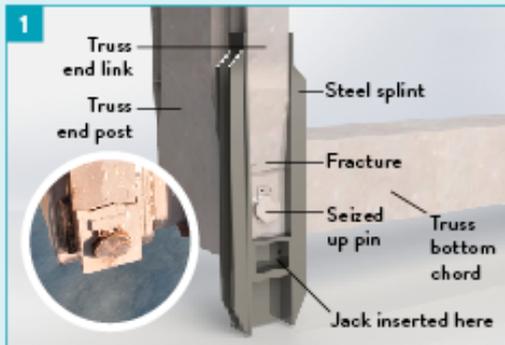
[zoom in](#)[zoom out](#)

The complete fracture of one element of the truss end link on the mains span section of the eastern leg of the north tower of the bridge, and the partial fracture of its counterpart, was discovered as part of a routine inspection. The bridge was closed the next day. Contractor Amey was already on site carrying out maintenance work on other areas of the bridge, and so stepped up to fix the problem.

The first stage was to carry out a series of inspections, but with access to the underside of the bridge severely limited, initial inspections were carried out via rope access. The team then designed and installed a bespoke scaffolding system to allow safe access to the members.

As fortune would have it, specialist monitoring company Strainstall was working on the nearby Queensferry Crossing project when the defect was discovered. A team of its engineers was diverted to the Forth Road Bridge to install a full structural health monitoring system on the stricken bridge. This included more than 200 strain gauges, along with temperature and tilt sensors to measure the stresses and strains in the bridge members.

## FORTH ROAD BRIDGE REPAIRS EXPLAINED



### 1 | PHASE ONE

A splint is created around the link to close the crack and restore its structural capacity.

Image: Amey

### 2 | PHASE TWO

A 9.5m high frame is installed above the deck to support the truss, removing the traffic load from the failed member and allowing the bridge to reopen to traffic.

Image: Arup

### 3 | PHASE THREE

A new bracket and bearing are installed to support the truss, eliminating the link.

Image: Arup

Screen shot 2016 11 07 at 15.29.53

[zoom in](#) [zoom out](#)

“Inside each of the towers there is a data acquisition unit. Each one is about the size of a fridge, and basically interprets the strain gauge data,” says Amey account director for Forth bridges Mark Arndt. “These were designed and installed in that three week period. That’s probably one of the most sophisticated systems on any bridge, certainly in the UK.”

With the bridge closed and the health monitoring system in place, the contractor carried out controlled load testing to investigate the stresses in the members and devise a solution to the problem.

To provide a temporary solution, a set of specially designed steel splints was welded to the sides and the bottom of the truss end link, forming a U shape around it. A gap was left between the bottom plate of the splint and the underside of the link member, allowing a jack to be inserted to lift the lower section of the truss end link.

The jack then closed the 20mm to 25mm gap created by the fractured parts, effectively restoring the end link’s original load bearing capacity.

Just three weeks after the problem was discovered, the bridge reopened to all traffic except HGVs on 23 December 2015.

Arndt says it was remarkable that all of the strengthening work and sensors were installed within three weeks. “That’s a process which would normally take a year to 18 months. During that time design checks were needed and approvals had to be given. Nearly 100 rope access technicians were needed, and work was disrupted by four storms.

Around 79% of the loading on the bridge is due to the dead load of the structure, another 7% is due to wind, 7% is temperature and 7% is traffic

Mark Arndt, Amey

“Then you have the backdrop that when you come into work the car park was full of BBC and Sky News reporters and so it was quite daunting for people.”

But the team could not rest. The root cause of the failure had not yet been established and haulage companies were applying pressure for the bridge owner to quickly come up with a more permanent solution.

With Christmas all but cancelled, phase two began.

“Around 79% of the loading on the bridge is due to the dead load of the structure, another 7% is due to wind, 7% is temperature and 7% is traffic,” says Arndt.

### **Open to cars**

“The reason why we could open it to cars is because they’re almost insignificant compared to HGVs.”

To look at ways to enable HGVs to start using the bridge again, the team used the live monitoring system to get real-time feedback on the behaviour of the bridge when it had reopened to cars.

The results of the load testing showed that HGVs could start to use it, albeit in regulated flows and only at night. “We could have HGVs on the bridge if we controlled them. If you had a convoy one after another, that was bad,” says Arndt. “Therefore we had a pulsed system with traffic lights to release a lorry every 30 seconds to merge with the free flowing traffic.

### **Traffic monitoring**

“To mitigate the risk of any incidents and avoid that bunching effect, we had spotters along the bridge who immediately radioed back to the control room [if bunching occurred] and the traffic was stopped.”

Monitoring also enabled the team to discover the root cause of the truss end link failure. The pin at the bottom of the link had seized up.

This meant that instead of the member rotating around the pin, it remained rigidly fixed, bending with the movement of the truss – a condition which it would not have been designed for. Over time this caused the member to become fatigued and eventually fracture.

“During phase one, we had carried out about 150 controlled load tests that involved a combination of gritter vehicles and a number of 44t trucks from a supply chain partner. We positioned these at specific points on the bridge, and from the analysis model we knew what the theoretical loading should be, so we could determine the degree of fixity of the pin.”

### **New link bypass**

To prevent another failure occurring and allow HGVs unrestricted access across the bridge, a new way of bypassing the link to support the deck truss had to be found.

To do this, the team bolted a 4.4m tall steel frame to the main tower above the deck and from this, the truss is now supported by two parallel strand jacks. These thread through the deck to the underside of the top chord of the truss.

But this was not without its own challenges.

“That was a much more complicated design because of the specialist components,” Arndt explains.



Forthbridge(6) phase two works complete

Phase two works involved attaching a temporary frame to the tower

“The cables themselves were highly specialist, as were the sockets. Again there was a mammoth effort to source these as fast as we could. The only place we could get the cables was France. The sockets came from Germany, and Belgium was the only place which could fabricate them.

“We then had people trying to weld in the freezing cold and physically trying to get huge beams into there was very difficult.”

The bridge opened to all traffic on 20 February just two and a half months after the initial fracture was found. But work to strengthen the bridge is still ongoing.

### **Third and final phase**

The team is now working on the third and final phase of the work. Permanent brackets will be installed on each of the tower legs to support the truss from underneath, eliminating the truss end links entirely. This will also allow the team to remove the steel frame which had been installed above the deck during the phase two works and restore the bridge to its original category A listed appearance.

On each bracket sits a bearing. This bearing is now presenting a series of complicated challenges. For a start, under certain load conditions, it has to resist uplift, which in combination with providing a low friction sliding surface is not commonplace. The bearing surface must also be able to be replaced while still providing support to the truss.

“Normally you get 50km of travel out of a bearing, but this bridge moves all the time, so how do you quantify how much of that has been achieved? So by using the monitoring, we’ll know how much it’s moving and design around that,” says Arndt.

### **Complex structure**

The connection of the brackets to the tower is also complicated by the tower’s structure.

It is a cellular steel structure wrapped in a steel skin and there are voids behind the locations of the two brackets. The external skin is too weak to take the loads exerted on the brackets, so the team has come up with a solution that involves filling the voids with reinforced concrete. Macalloy bars are then inserted through the tower structure into the concrete to take the loads from the new brackets.

“It’s 5t for the bearing itself, the bracket is 7t, so it’s massive, and then it’s got to support 400t of traffic loading,” says Arndt.

### **Tricky concrete pour**

“There were several concerns,” says Arndt. “It’s heavily reinforced, so can you get steel fixers in, and, more importantly, out of the confined space? And then the concrete, could that flow into the tower without voids forming?”

To get answers to these questions, the team built a 5m high replica of the tower and has used it to help it design a high strength, high flowability, self-levelling and self-compacting concrete. “The last thing we wanted to do was try it out on the bridge and find it didn’t work,” he says.

Work to install the first bracket and bearing is expected to be finished by the end of the year, weather permitting. The remaining seven links will be replaced in turn.

### **Feeding the media**

The success of the project also depended on the constant flow of information to the media, the regular users of the bridge, and the Scottish Government. Initial anger at the bridge’s closure quickly turned to support when Amey published its findings and extensive plans for its repair.

Such was the turnaround in attitudes that by the end of the works, any negative feedback left on Twitter was immediately set upon by hundreds of now loyal fans.

“We shared everything,” says Arndt. “In the early days it was very negative, people didn’t expect it to close.

“It was in the run up to Christmas so all the connections to Edinburgh and the festivals were affected, but through the social media campaign the public got behind it and they saw what conditions the workers were operating in almost every hour of the day, doing what needed to be done.

“At the time, it was one of the worst experiences in my life, but in retrospect, one of the best.”