The innovative bearing solution engineered for the Forth Road Bridge's modified deck-to-tower connections

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Abstract

Opened in 1964 as the longest-span suspension bridge outside the USA, the Forth Road Bridge is a crucial connection between south-east and north-east Scotland. Greatly increased traffic loading caused a fatigue fracture, in December 2015, in one of its eight truss end links which support the deck ends at the towers, resulting in the closure of the bridge. Following implementation of an emergency repair to enable the bridge to re-open quickly, it was necessary to implement a reliable long-term fix to avoid a re-occurrence at any link location. An innovative solution was developed, incorporating free-sliding bearings designed to resist high uplift forces and accommodate large deck movements and significant rotations, with adequate durability considering the bearings' very long cumulative sliding path of 16 km per year. The bearings were also required to be pre-fitted with structural health monitoring sensors. The challenge and the solution are described.

Keywords: Forth Road Bridge; Truss End link; repair; bearing; integrated SHM.

1 Introduction

The Forth Road Bridge (total length 2512 m, main span 1006 m) across the Firth of Forth estuary in Scotland – one of the United Kingdom's greatest obstacles to land transportation – was opened to traffic in 1964 having been designed for the traffic standards of the day. Fifty years later, traffic volumes had more than doubled to approximately 70,000 vehicles per day, with design vehicle loading also doubling from the 22-tonne rigid truck of the time to today's 44-tonne articulated truck. In December 2015, following many years of service, subjected to this greatly increased loading, an element of the steel deck's superstructure was found to have failed and the bridge was closed to traffic. The element was a so-called Truss End Link, which linked the bottom of a section of steel deck truss, at its end, to the tower that supported it. With two truss end links (one at each side of the deck) at each side of each of the two bridge towers, the total number of truss end links was eight. One of these elements is shown in Figure 1.

Following the carrying out of emergency measures to enable the bridge to be re-opened to traffic as quickly as possible – for which Amey plc, under a five-year contract from Transport Scotland to manage and maintain the bridge, received the prestigious *Greatest Contribution to Scotland Award* at the 2016 Saltire Society Civil Engineering Awards – it was necessary to implement a long-term solution. Following the evaluation of various options, it was decided not to replace the truss end link with a similar element, but rather to develop a more reliable solution with the bottom of the partially renewed truss supported by a bearing. This solution is illustrated in Figure 2, and the eight relevant locations are shown in Figure 3.

Figure 1. Illustration showing a Truss End Link (highlighted) at end of one section of deck truss. Pins at both ends allow the link element to rotate, enabling deck movements to be accommodated

Figure 2. Illustration showing developed solution (highlighted) with part of deck truss replaced and supported by a new bearing on a new support bracket which projects out from the tower

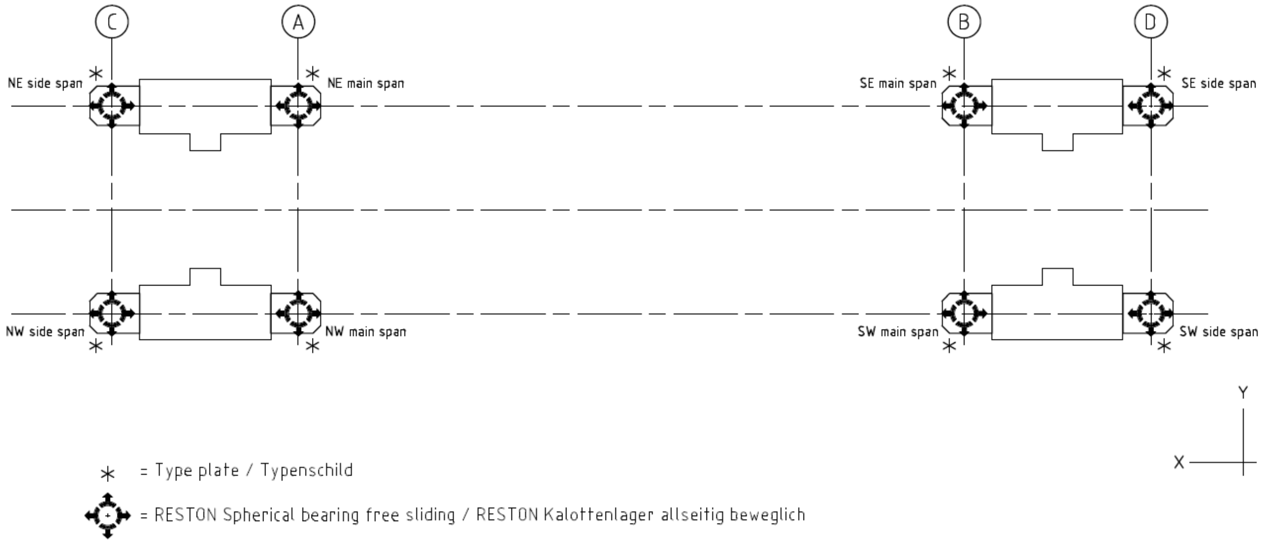

Figure 3. Schematic drawing showing locations of the eight required bearing solutions

Lasten nach: / Loads according to: EN 1991-2 / EC 1			Lastfall A / Load case A		Lastfall B / Load case B		Bewegungen / Movements			
Ort / Location	Typ / Type	Zeichnung / Drawing	$N_{Ed,max}$	$V_{Ed,max}$	$N_{Ed,min}$	V_{Ed}	u_x ±	e_{ux}	u_y ±	e_{uy}
NE main span	KA6.6-Upl	KA6.6-Upl-1-GB-350074	6'680	-	-2'755	-	1015	0	70	0
NW main span	KA6.6-Upl	KA6.6-Upl-1-GB-350074	6'680	-	-2'755	-	1015	0	70	0
SE main span	KA6.6-Upl	KA6.6-Upl-1-GB-350074	6'680	-	-2'755	-	1015	0	70	0
SW main span	KA6.6-Upl	KA6.6-Upl-1-GB-350074	6'680	-	-2'755	-	1015	0	70	0
NE side span	KA5.7-Upl	KA5.7-Upl-1-GB-350074	5'735	-	-2'535	-	515	0	25	0
NW side span	KA5.7-Upl	KA5.7-Upl-1-GB-350074	5'735	-	-2'535	-	515	0	25	0
SE side span	KA5.7-Upl	KA5.7-Upl-1-GB-350074	5'735	-	-2'535	-	515	0	25	0
SW side span	KA5.7-Upl	KA5.7-Upl-1-GB-350074	5'735	-	-2'535	-	515	0	25	0

Figure 4. The key loads and movements for which the bearings required to be designed

2 Key bearing design requirements

The key loads and movements for which the bearings required to be designed are summarised in Figure 4. As shown, the four main span bearings each required to be designed for downward forces of 6,680 kN and uplift forces (very infrequent) of 2,755 kN, with longitudinal movements of +/- 1,015 mm and transverse movements of +/- 70 mm arising. Rotations of 0.007 rad about the x-axis, 0.042 rad about the y-axis and +/- 0.0487 rad about the vertical z-axis also had to be allowed for. The four side span bearings required to be designed for somewhat lower forces, movements and rotations.

In terms of longitudinal sliding distance, it is not only the absolute movement capacity of +/- 1,015 mm that is very substantial, but also the cumulative sliding distance over time, which was estimated at 16.1 km per year – at speeds of up to 4.75 mm/s.

To protect sliding surfaces against dirt and debris, it was specified that all main sliding surfaces must be protected by a removable screen or shroud.

It was also specified that sensors for a structural health monitoring (SHM) system be integrated in the bearings' design and fabrication. These sensors would then require to be connected to the bridge's existing overall SHM system, following installation of the bearings on site.

3 Design of the bearings

The design of these special bearings presented a significant challenge in optimising solutions that would meet all specified performance requirements (in terms of forces, movements, rotations, etc.), and ensure the highest quality and durability, while also minimising weight and thus avoiding unnecessary loading on the main structure and the support connections, and reducing installation difficulties.

Having considered the suitability of various different types of bearing on which the solution should be based, it was decided to develop a solution from a standard spherical bearing design.

3.1 The spherical bearing

Spherical bridge bearings are based on the principle of a steel calotte, with the shape of a spherical cap (a portion of a sphere cut off by a plane), located within a concave-shaped steel part with a matching radius. The calotte can rotate freely within the concave part, thus enabling the bearing to efficiently facilitate large bridge deck rotations. Like other types, spherical bearings can be designated fixed, free sliding or guided sliding, depending on their ability to accommodate horizontal sliding movements or resist horizontal forces: the fixed type does not allow sliding movements (translations) in any direction, but rather resists all horizontal forces; the free sliding type allows sliding movements in every direction (resisting no horizontal forces); and the guided sliding type allows sliding movements along one horizontal axis, but resists forces transverse to this. The build-up of each of these types is shown in Figure 5, and further illustrated by the images in Figures 6 and 7.

Figure 5. Exploded views of spherical bearing types (from left: fixed, free sliding and guided sliding)

Figure 6. Assembly of a fixed spherical bearing

Figure 7. A guided sliding spherical bearing

Spherical bearings are very strong and durable, consisting entirely of carbon steel, stainless steel and a sliding material such as PTFE above and below the calotte. The weakest part is the sliding material, so the strength and durability of the entire bearing depends on that of the sliding material (unlike, for example, a pot bearing, the strength of which is also limited by the elastomeric pad at its core). The use of an alternative high-grade sliding material such as Robo-Slide (see below) can substantially increase the load carrying capacity of the bearing, and offers further benefits as described below.

3.2 *Robo-Slide* sliding material

Robo-Slide (Figure 8), a patented sliding material of modified UHMWPE (ultra-high-molecular-weight polyethylene), was specially developed and certified for use in bridge bearings and expansion joints, and offers several advantages over the traditionally used PTFE. It has a high characteristic load capacity of 180 N/mm^2, double that of PTFE. It also offers far higher resistance to wear – in testing, virtually no signs of wear were detected after a sliding distance of 50 km, while PTFE suffered significant loss of thickness after just 10 km (Figure 9). And at high pressures and/or low temperatures, the friction coefficient of Robo-Slide is lower than that of PTFE, resulting in lower transverse forces on the connecting structures – a fact that is likely to be significant for the design of many bridges, because the transverse forces arising at high pressure and low temperature are likely to be defining in the design of supporting piers etc.

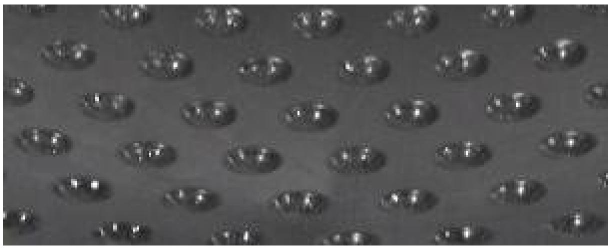

Figure 8. Close-up view of Robo-Slide (with grease dimples) – a high grade alternative to PTFE for bearings and expansion joints

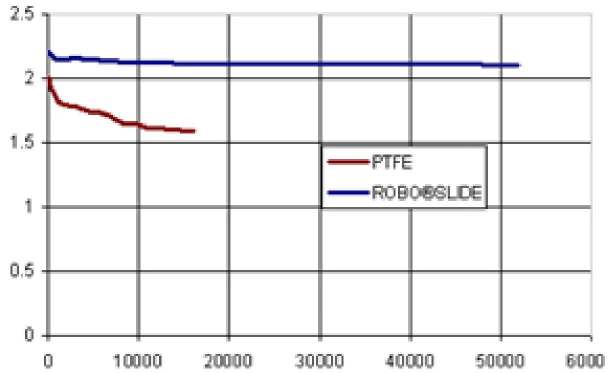

Figure 9. Resistance to wear of Robo-Slide and PTFE – measured by height of bearing's sliding gap [mm] following large total sliding movements [m]

The material can also be used at very low temperatures (as low as -50°C), and at high temperatures (up to approximately 50°C).

With grease dimples and high-performance grease, a durable, low-friction sliding surface can be ensured. Wear and local overstressing are also minimised by the material's excellent formability, which enables it to accommodate irregularities in the supporting structure. And resistance to aggressive chemicals and high-energy radiation are also excellent. All of this minimises bearing maintenance and replacement costs.

The use of this sliding material on spherical bearings has been extensively tested to prove performance and durability. The *Reston-Spherical* bearings proposed for use on this project, with Robo-Slide sliding material, are certified (European Technical Approval 08/0115) for use in Europe by the German Institute for Construction Technology (DIBt), on behalf of the European Organisation for Technical Approvals (EOTA).

3.3 Project-specific design

An illustration of the bearing design is presented in Figure 10. The calotte and concave element of the standard spherical bearing are barely visible, above the T-beam and below the upper steel plate.

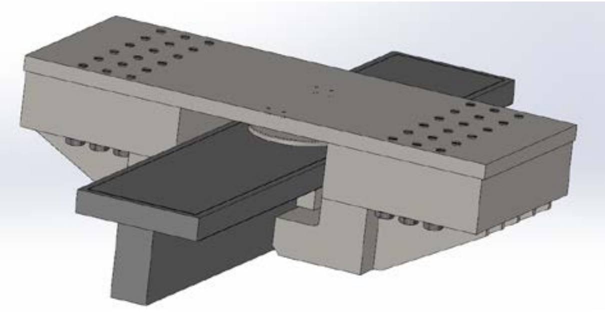

Figure 10. Illustration of the developed bearing design, with the calotte etc. of a standard spherical bearing at its heart

Figure 11. Completed solution, with new bearing installed and supporting the deck truss. One end of the bearing's T-beam, at the tower, is enclosed in a protective expanding/contracting shroud

Due to the very large longitudinal movement requirement of +/- 1,015 mm, a long sliding plate was required. This plate, to be covered by a stainless steel sliding sheet, is provided in the form of the T-beam shown in the illustration, which has a length of approximately 2.5 m. With the bottom of the T-beam securely connected on site to the bracket newly projecting from the side of the tower (as can be seen in Figure 11, which shows an installed bearing), it was not necessary to provide this beam with a lower flange, avoiding unnecessary costs and weight.

To resist the large uplift forces of up to 2,755 kN, large uplift lugs (with sliding strips to accommodate sliding during uplift conditions) are provided at both sides of the T-beam. Due to the rareness of uplift conditions, with an estimated frequency of just one occurrence per year, it was not necessary to design the bearings with pre-compressed sliding interfaces – a measure that is necessary in cases of frequent load reversal between downward and uplift conditions to prevent hammering at the sliding interface and destruction of the sliding materials.

All parts are dimensioned to allow also for the additional transverse movements and the specified rotations about all axes (including vertical). Examples of dimensional checks carried out to ensure no clashing of elements in the most adverse loading / movement / rotation combination cases are presented in Figures 12 and 13.

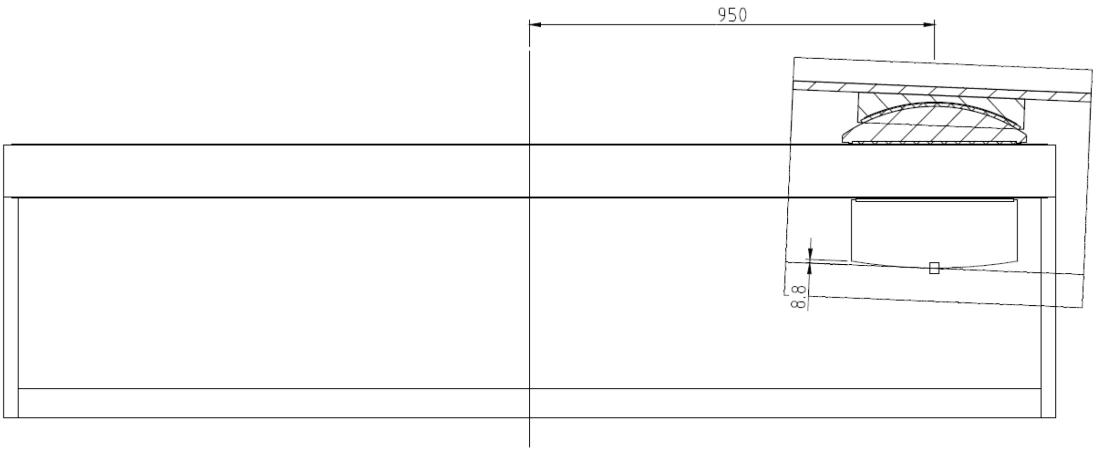

Figure 12. Dimensional check of large rotation combined with large longitudinal movement

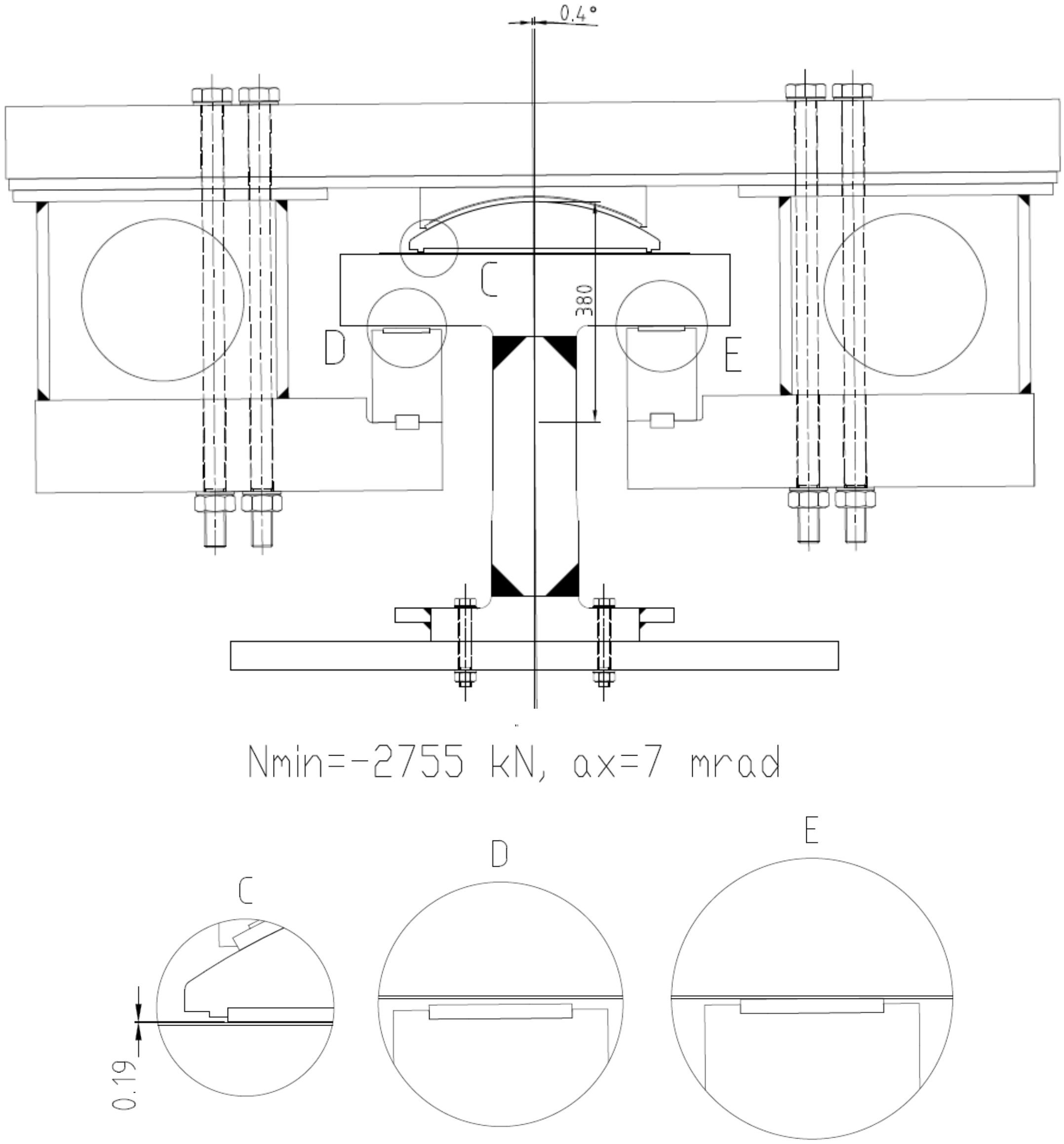

Figure 13. Dimensional check of rotation about longitudinal axis during maximum uplift load

Considering the unusually long cumulative sliding distance of 16.1 km per year to which the main span bearings would be subjected, and the speeds of these movements (at up to 4.75 mm/s), the choice of sliding material became a very important factor in the bearing design. Given that PTFE, the sliding material traditionally used in sliding bridge bearings, typically shows signs of serious deterioration after a cumulative sliding distance of just 5 to 10 km, it is clear that an alternative sliding material is required in a case like this. Therefore, the bearing supplier's far superior alternative, the modified UHMWPE known as *Robo-Slide* (refer to Section 3.2 above), was used instead, as one part of a proven tribological system, in combination with high-quality stainless steel and bearing quality silicone grease.

To help keep the main sliding surface free of dirt and debris – an especially important objective considering the "upside down" orientation of the bearings with the sliding plate on the bottom – a folded sheet / "bellows-type" protective screen was provided in two parts for each bearing. These screens can expand and contract as the bearings are subjected to longitudinal movements, and were designed to cover the complete length of the sliding sheet, regardless of the movement currently experienced by the bearing.

4 Fabrication

Manufacturing of the individually shaped I-beams presented particular challenges, with large weld seams subjected to high demands such as the use of Z-grade steel and minimum notch toughness of 47 J at -20 C°. Some of the related components' plates, with thicknesses of up 180 mm and lengths of up to 2.5 m, were welded together with more than 100 individual layers. To maintain the required ductility for the final product, the sliding plates were continually pre-heated by an inductive pre-heating system. Finally, these elements were heat-treated and 100% tested by ultrasonic and magnetic particle examination methods.

Images from the fabrication of one bearing, further illustrating its design, are presented in Figures 14 to 16.

Figure 14. View of top of longitudinal T-beam, with stainless steel sliding sheet applied to top surface and calotte of spherical bearing positioned on top

Figure 15. Placing of top plate with uplift clamps hanging down around the T-beam's top flange

Figure 16. A completely fabricated bearing, secured to a pallet for transport to site

5 Structural health monitoring

As specified, the bearings were supplied with pre-integrated sensors for a structural health monitoring system. These sensors, required to be connected to the bridge's existing overall SHM system, were required to measure:

- Depth of remaining sliding surface (indicating wear of the sliding material)
- Bearing rotation (about both axes)
- Bearing movements
- Loads (downward vertical).

This was achieved by the integration in the bearing, at suitable locations, of draw-wire sensors, inclination sensors, inductive sensors and pressure sensors.

As agreed with the client, the sensors' selection and design and their integration and proper functioning in the bridge's existing SHM system was first checked on the first bearing installed. Then, with the benefit of experience gained / lessons learned from this first application, details were finalised for the remaining bearings.

Images from the pre-integration of the sensors in the bearing during fabrication in the factory are shown in Figures 17 to 19, and cabled connection to the bridge's SHM system is shown in Figure 20.

Figure 17. Two laser distance sensors at one side of bearing's concave rotation element, for monitoring the width of the bearing's sliding gap and thus wear of the sliding surface

Figure 18. Testing of a piezoresistive pressure sensor following integration in a bearing

Figure 19. An analogue encoder with cable pull / magnetic sensing for monitoring of longitudinal movements

Figure 20. Following installation, connection of a bearing's integrated sensors to the bridge's existing SHM system by means of suitable cabling

6 Conclusions

Following the rapid execution of emergency repairs to the Forth Road Bridge in December 2015, as necessitated by the sudden failure of one of the structure's eight truss end links, it was necessary to ensure that similar problems would not arise in the future. The innovative long-term solution developed and implemented by Amey plc provides great confidence in this regard, and necessitated the application of in-depth engineering know-how and experience – not least in relation to the bearings that are central to the solution. This project demonstrates, once again, how exceptional engineering structures, and extraordinary bridges in particular, often require unique, innovative solutions – solutions which can only be provided by suitably experienced suppliers.