

The Bandra-Worli Sea Link – Mumbai’s new landmark with locally supplied key components

T. Spuler, G. Moor & C. O’Suilleabhain
Mageba SA, Bulach, Switzerland

S. Majumdar
Mageba Bridge Products Pvt. Ltd, Kolkata, India

ABSTRACT: The final completion in March 2010 of the Bandra-Worli Sea Link marked a significant leap forward in the bridge engineering capabilities of the Indian subcontinent. The structure, with a length of 5,600m, is the first open sea cable stayed structure of its kind and features locally supplied key parts which in the past would have had to be imported from far afield. The disc bearings manufactured for the bridge by the local subsidiary of an international supplier represented the first use of disc bearings in this part of Asia, while the company also supplied the expansion joints required by the bridge’s entire length. Benefiting from the decades of experience previously amassed by the parent company, the new local operation could quickly become proficient in the manufacture of these complex constructions, providing a manufacturing base in this region for the most technologically advanced bearings and expansion joints in the world.

1 INTRODUCTION

Advancement in science, engineering and technology is a continuous process with emerging new ideas, innovations and applications which are accepted through time-tested success. Like any other civil and construction engineering areas, progress in bridge bearing and expansion joint technology during the last century has been remarkable. Bearings and expansion joints are vital safety items and play a major part in life and performance of the entire bridge, though their cost is rather insignificant compared to the total bridge project cost.

The prime objective of bridge engineers is to develop efficient solutions catering for the needs of demanding modern-day long-span bridge structures, ensuring long structure life to serve future generations. Presently, the thinking of bridge engineers is greatly influenced by the fact that, with recent rapid advances in bridge bearing technology and material science, there are many options to choose from, providing the designer considerable freedom to elevate the state-of-the-art modern day bridge design, reducing overall cost, extending the maintenance-free life and reducing risks from major ground movements and seismic accelerations.

This fact is becoming more and more appreciated and stressed, and new bearing and expansion joint systems are being used considering various aspects such as design, location, atmospheric conditions, terrain, soil conditions, volume and type of traffic, aesthetics, and many other socio-economic and environmental factors. Local availability of the latest technologies in the field of bearing and expansion joint systems are also becoming extremely important. Locally sourced systems are normally subjected to rigorous quality control tests, simulating the actual site conditions to ensure quality level comparable with the best of its kind available anywhere in the world.

2 BACKGROUND

Mumbai and its suburbs have a total population approaching 13 million, making it the second most populous conurbation in the world after Shanghai. It suffers from similar woes as other heavily congested cities like

Sao Paulo, Mexico City and Bangkok with respect to clogged traffic and prolonged congestion. With the advancement of the local economy and the rise of a huge middle-class population, the situation has gotten continually worse.

Since the late 1990's the local authorities in Mumbai have undertaken ambitious plans to construct several flyovers, underpasses, tollway corridors and sea links across bay water bodies to ease the congestion and many of the projects are already implemented. One such project has been to connect the Bandra and Worli points across Mahim Bay (Figure 1) by a 5.6 km long tollway bridge with eight traffic lanes for the exclusive use of fast moving vehicles, thus opening a north-south corridor known as the Bandra Worli Sea Link, now re-named 'Rajiv Gandhi Setu' since being opened to traffic. It consists of a cable stayed bridge of 500m main span over the Bandra Channel and a second cable stayed bridge of main span 150m over the Worli Channel. The new sea crossing has already made an enormous contribution to easing congestion on the busy roads of this metropolis, where the provision of new infrastructure has struggled to keep up with the explosion in the amount of traffic on the city's roads.

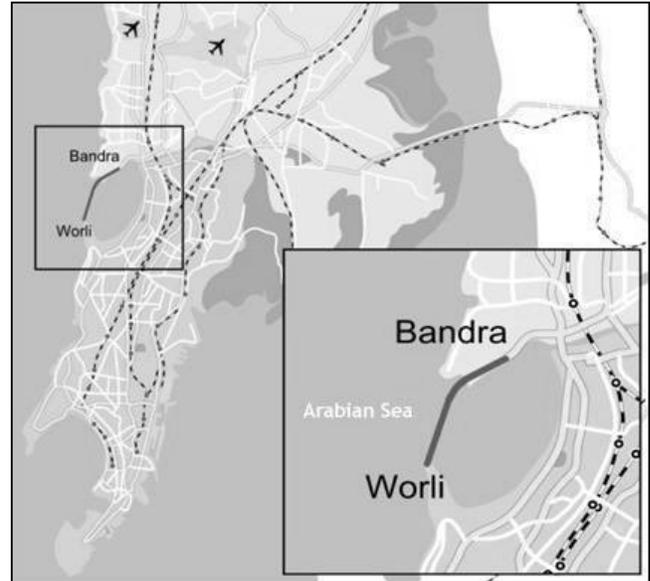


Figure 1. Location Map of the Bandra-Worli Sea Link

The government also has ambitious plans to connect Worli with Nariman Point across the sea and also to connect Sewri in South Mumbai to Nhava in Navi Mumbai over the sea with an eight-lane (two-way, four-lane) highway bridge, the Mumbai Trans Harbour Link (MTHL) bridge which will be India's longest sea link project, a 22.5-km long bridge over the sea.



Figure 2. Bandra-Worli Sea Link during construction

Initial design of the Bandra Worli Sea Link project was conceived by an eminent US-based consulting company, who introduced latest innovations and techniques of modern day engineering in their concept. Based on their experience in the USA and other countries, advanced bearings and expansion joint systems were proposed by the consultants, posing a number of challenges to the bridge constructors, not least among them in terms of sourcing the components for the first time use in India.

3 SELECTION OF BEARINGS –COMPARISON OF OPTIONS

During the late 1950's a new generation of compact, high load capacity, multi-rotational bearing devices were developed, beginning with the confined elastomer or "pot" type bearing by the German engineers Andrä, Beyer and Wintergerst, to satisfy the need for a new bearing that would accept high loads with minimum peak stress on supports, minimal vertical deflection, multi-directional rotational capability with lower rotational resistance, low profile, maximum reliability and minimum cost for structures.

While pot bearings have been installed successfully on numerous structures throughout the world, several problems have surfaced, primarily because of limited dependable and suitably qualified manufacturing sources but also, in some cases, due to indiscriminate use without a thorough understanding of behaviour and limitations.

The concept of the pot bearing is based on effectively confining the elastomer within a metallic piston-cylinder arrangement so that the elastomer remains in a state of uniform strain and no tension is produced while subjected to very large compressive stress. Unlike a traditional laminated elastomeric bearing, such a perfectly confined elastomer, while subjected to large compressive stress, behaves like a viscous fluid and is therefore able to cater for a high degree of multi-directional rotational movement. Extremely tight tolerance of manufacturing is required, together with a well detailed and very effective sealing system in order to confine the elastomer properly. If the steel piston is manufactured with the same diameter as the base pot, a condition of steel-to-steel contact will develop which inhibits the rotational capacity of the bearing. When the piston is manufactured with diameter not close enough to that of the base pot, the sealing ring has difficulty containing the elastomer which under the design pressure acts like a fluid.

There have been a number of problems around the world with pot bearings due to inadequate design, incorrect raw materials and poor production techniques. In some cases, leakage of the elastomer has been noticed even with bearings that were apparently well manufactured. Abrasion or wear of the elastomeric pad has also been noticed in some cases. A number of reasons have been postulated for these problems, including: inadequate clearances or tolerances between the piston and cylinder; excessive rotation angle, rotation cycles or lateral load; abrasion of the sealing ring; deformation of the pot due to excess lateral load or gravity load; inadequate (or excessive) lubrication of the elastomer pad; and inadequate surface finish of the portion of piston/ cylinder in contact with elastomer pad.

Moreover, satisfactory rotational distribution is not achieved until at least 25% of the bearing load capacity is applied. The rotational resistance of the confined elastomer pad, though not negligible, is often ignored due to lack of understanding of behaviour of the pad and in some cases due to absence of data. Another problem with the pot concept has been experienced in colder climates. This deals with the rotational element typically being manufactured from synthetic rubber (chloroprene rubber). At extremely cold temperatures, coupled with high-design pressures, the rotational element has been known to crystallize, which in turn eliminates the rotational capacity of the device. None of these effects or deficiencies in the confined elastomeric pad element in a pot bearing can be visually detected during service unless the bearing is removed and the elastomeric pad is taken out of the bearing for inspection of the elastomeric element, metallic cylinder and piston.

Many cases of such failures have resulted in authorities now preferring traditional steel bearings or alternative advanced bearing systems such as disc bearings and spherical bearings with high-performance sliding material. The above concerns have in particular resulted in the *American Railway Engineering and Maintenance-of-Way Association (AREMA)* restricting the use of pot bearings in their field, stating that "pot-type multi-rotational bearings should not be used for support of railroad bridges due to concerns over large cyclical live load deformations and rotation". Many countries in Europe have also restricted use of pot bearings for the same reasons.

Disc bearings with in-built shear restriction mechanism were developed in the USA in the 1970's. Pasco Kennewick Inter City Bridge in the State of Washington is considered to be one of the earliest major projects in which disc bearings were used. This cable-stayed bridge has an overall length of 762 meters (2500 ft.) and a main span of 296 meters (970 ft). Disc bearings with vertical load capacities ranging from 2,670kN to 12,400kN and with movement capacities of up to 660mm were installed in this landmark structure in 1976. The bearings were inspected in October 2001 and found to be in excellent condition, even after 25 years of service.

A disc bearing features a highly durable moulded polyether urethane rotational element at its core, which can be subjected to very high stresses while facilitating significant rotations. The result is a simpler bearing than the alternative which it could in many cases replace, the pot bearing. The disc bearing can accommodate comparable stresses and rotations but due to its simplicity, offers a solution which has the potential to result in fewer maintenance problems and bearing failures.

Polyether urethane compound is a high-strength, aromatic thermoplastic and is distinguished from many other elastomers by their excellent mechanical properties, allowing a polyether urethane disc to be subjected to high levels of stress. Due to its high compressive strength, the rotational element moulded from polyether urethane compound requires no need for confinement (see Figure 3). This provides the major advantage that the behaviour and physical condition and shape of the open disc can be observed during factory testing and also periodically during service. The problem of insufficiently sealing sometimes suffered by the elastomeric pads of pot bearings is also absent in disc bearings.

At the service limit state, the average compressive stress on the disc of a disc bearing may be as high as 35 MPa. The polyether urethane disc does not undergo plastic deformation until about 20 times the allowable load limit is applied. This means that the disc has a huge in-built safety factor when subjected to vertical loads. Since the actual design load on the disc is quite low compared to its actual capacity, the long-term creep is very low, adding considerably to the life and performance of the disc bearing as compared to a pot bearing.

A major disadvantage of the elastomeric pressure pads of pot bearings is crystallization at low temperatures and brittleness at high temperatures. Also, the elastomeric material is susceptible to a large range of variation of ambient temperature. The urethane material of the disc bearing, on the other hand, remains flexible and operational without any permanent physical or chemical transformation, softening, brittleness or crystallization for a wide range of ambient temperatures, e.g. from -700°C to $+1210^{\circ}\text{C}$ i.e., a range as wide as 1910°C . Prolonged tests and research carried out by DuPont has also proved that the disc material has excellent weathering properties compared to the elastomeric material of the pot bearing, even when subjected to continued exposure to severe atmospheric conditions such as corrosive marine atmosphere, ozone and other destructive chemicals, gas, etc.

In view of the above the consultants chose disc bearings for the Bandra-Worli Sea Link over the commonly used pot bearings. As many as 226 fixed and unidirectional DISKTRON® Disc bearings with vertical load capacities of up to 14,000kN have been installed in this landmark bridge.

4 SOURCING OF DISC BEARINGS

Although the disc bearing was new to the Indian subcontinent, it was possible to source locally thanks to close cooperation of a local manufacturer with leading bearing suppliers from Europe and the United States. The highest standards were set for manufacturing and in-house testing of the bearings by the manufacturer to meet the stringent project specification and quality requirements. Bearings from each supply lot were tested for proof load, rotation and dynamic coefficient of friction (Figure 4). The full-scale tests conducted for each supply lot have established that the actual behaviour of the polyether urethane rotational disc element closely resembles the linear elastic behaviour assumed in its design, thereby proving the reliability and functionality of the bearings.

The vertical load capacity of the disc bearings manufactured for this project ranges from 3,000kN to 14,000kN, with horizontal force capacity ranging up to 55% of vertical load capacity. A typical span arrangement for this project consists of modules of five-span continuous deck structure of precast segmental construction. Out of the six piers supporting each five-span continuous module, four fixed type



Figure 3. Typical configuration of a multi-directional Disc Bearing

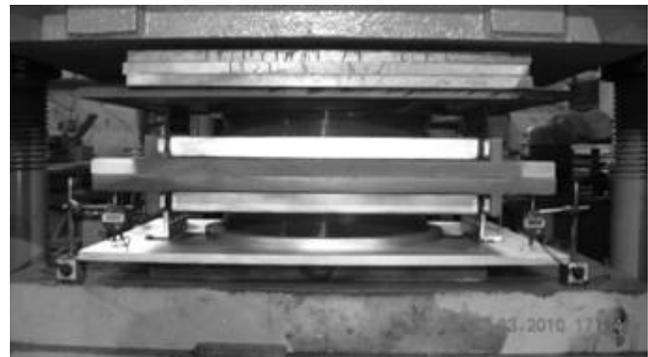


Figure 4. Load testing of Disc Bearing

disc bearings have been used on the two central piers and unidirectional sliding disc bearings on the other piers, thus total twelve bearings per module. Thanks to the perfect detailing of the bearings to suit the method of construction of the bridge, the pier segments could be erected directly on the bearings, followed by subsequent erection of the segments and pre-stressing (Figure 5). During the construction stage, the bearings were subjected to 150% overloading for short duration.



Figure 5. Erection of bridge segment over disc bearing in Bandra Worli Sea Link

The bearings are exposed to very severe conditions because of the location of the bridge over open sea. The corrosion protection measures as originally specified were modified by adopting the most stringent specification as per system reference SC7Z of BS:5493, viz., sealed zinc spray of nominal thickness 250 microns, applicable for “Exterior exposed polluted coastal atmosphere” as well as for “Sea water splash zone or frequent salt spray” having very long (20 years) expected life to first maintenance. The seating surfaces of the discs as well as the surfaces in contact with the concrete structure have also been applied with zinc metal spray of nominal thickness 50 microns.

Disc bearings have demonstrated outstanding performance on bridges around the world for the past 40 years. The polyether urethane load and rotational element has proven to be a durable and functional key feature of these bearings, verified by field inspections of bearings after 30 years of service. Having now been used on this landmark structure in Mumbai, it is likely that disc bearings will henceforth be increasingly used across the Indian subcontinent, providing efficient solutions for the bearing requirements of today’s complicated bridge designs. Because of the disc bearing’s unique ability to adapt to a variety of loading conditions, their use for road and railway bridges looks certain to increase.

Following the success of the adoption of disc bearings for the Bandra-Worli Sea Link, a prestigious major bridge over River Hooghly near Kolkata viz. 2nd Vivekananda Bridge have also been equipped with disc bearings, including uplift resisting features, which were again sourced locally. The success story continues with disc bearings produced in India now being directly exported to the USA for the important Miami-Dade Metro project, meeting the highest quality standards and demanding schedule, proving the worldwide acceptability of disc bearings produced in India.

5 SOPHISTICATED AND WELL-PROVEN EXPANSION JOINTS

The long cable stayed spans, and the typical viaduct portion of the 5-span continuous modules of the Bandra-Worli Sea Link as described above, resulted in a large amount of deck movement. No fewer than 26 TENSA®MODULAR expansion joints were needed for the structure, with up to 6 gaps per joint and thus enabling up to 480mm of longitudinal movement. This type of joint is exceptionally accommodating, easily facilitating movements in all directions and rotations about all axes, and can be designed to allow longitudinal movements of a bridge's deck in excess of 2,000mm, far exceeding the range of most other types of joint.

In a modular expansion joint, a number of lamella beams divide the movement range at the end of a bridge deck into individual gaps, permitting easy passage of traffic (Figure 6). They are connected with special sealing profiles to form a water-tight unit.

All structural elements of the modular expansion joint for this project were made from high quality materials. Production was in accordance with the latest ISO 9001:2000 quality assurance requirements. Weld seams at highly stressed connections are avoided to ensure durability. Clever design facilitates the exchange of individual parts as necessary without difficulty. The modular expansion joints used in this project have no loose or moving steel components which would be susceptible to damage from frequent load changes. Movement and torsion are facilitated by lubricated PTFE and high-grade stainless steel, and by elastomeric components and plastics. The elasticity of the support system absorbs shocks and vibrations and also permits transverse movements. It also allows vertical movements and rotations.

The modular expansion joints used in this project have an elastic self-regulating gap control system. This system increases the durability of the whole structure, because it helps to absorb the dynamic loads from traffic passing over it. Any potential damage to the structure caused by the “blocking” of an individual gap (e.g. by trapped debris) is effectively averted due to the independent elasticity of the control system.

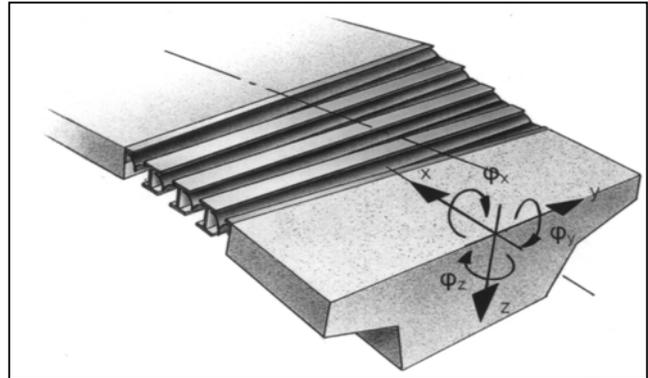


Figure 6. The modular expansion joint used accommodates movements in all directions and rotations about all axes



Figure 7. Opening Movement & Vibration (OMV) Test

The OMV Test simulates the most common movement of an expansion joint, the movement due to the daily thermal expansion and contraction of the superstructure, by opening and closing the expansion joint with an actuator with a period of approximately 10 seconds (a frequency of 0.1 Hz). At the same time, traffic loads are simulated by attaching a powerful pneumatic vibrator to one of the lamella beams. The applied force of 45kN is approximately constant but changes its direction at about 100Hz, resulting in the vertical and horizontal components of the load varying in sinusoidal manner.

According to current AASHTO design requirements, the expansion joint must be tested for the equivalent of at least 75 years of 365 daily thermal cycles, or 27,400 cycles. At 0.1 Hz this is equivalent to 76.1 hours of actuator cycling. One cycle of +/-51mm longitudinal movement was considered equivalent to an average daily movement.

On inspection of all parts after this testing, including sliding bearings, sliding springs and control springs, and of factory and site welds, it could be confirmed that the tested expansion joint had retained its full functionality with all components performing well.

The laboratory testing reconfirmed what was already known from decades of experience in supplying modular expansion joints of the highest quality to countless bridges all around the world: The joint can be relied upon to perform well for its entire lifetime for this demanding structure, taking account in particular of movements due to thermal effects and of vibrations and loading from traffic.

Stringent corrosion protection measures, similar to those applied for the disc bearings of the bridge, were also adopted for the expansion joints. The TENSA®MODULAR joints have been successfully installed along the full length of the bridge, giving high riding comfort to the bridge's vehicular traffic (Figure 8).



Figure 8 Installed modular expansion joint of the Bandra-Worli Sea Link

6 LOOKING TO THE FUTURE WITH CONFIDENCE

The new Bandra-Worli Sea Link is a symbol of the great advances of the economy and engineering capabilities of the Indian subcontinent – not only because it is the sort of structure that could grace the skyline of any major city, but due to the involvement of developing local manufacturing which can compete with the world's best in the supply of complex structural components, another thread in the tapestry of the region's remarkable ongoing development as a powerhouse of the world economy.