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High damping rubber isolators: Application to bridges in Bangladesh

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ABSTRACT: Due to the rapid economic growth in South Asia, infrastructure projects are being developed to facilitate movement across the continent. Known to have large rivers and swamps, the region is expecting a boom in the number of new bridges to reduce transportation time and cost. Asia was hit by severe earthquakes that caused the loss of lives and damage to structures, including bridges. To mitigate earthquake hazards, engineers and scientists developed devices and methods to improve the seismic performance of bridges and increase its service life. This paper explains the recent advances in the development of seismic isolation systems focusing on rubber bearings, the benefits of its implementation to bridges and examples of its application to bridges in Bangladesh. Improvement of long-term durability and ozone cracking resistance of rubber bearing and the installation of the bearings to the 2nd Kanchpur, Meghna, and Gumti Bridges are discussed.

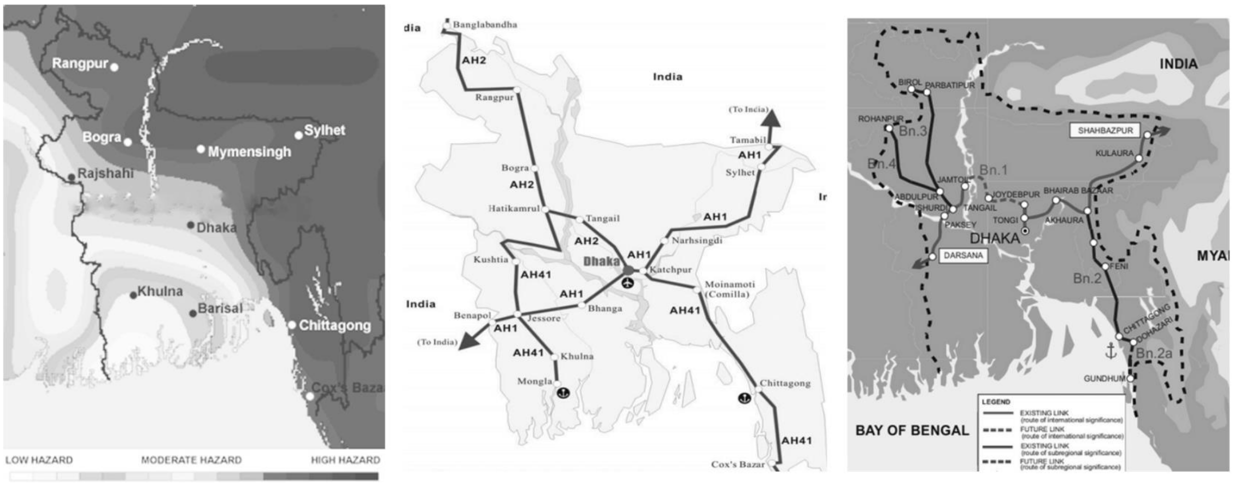
1 INTRODUCTION

1.1 *Bangladesh and Earthquakes*

Bangladesh is not familiar with strong earthquakes but in the summer of 1918, an earthquake hit the northeast region of Bangladesh. The earthquake caused unprecedented damage to structures and caused disturbance to the population. The few strong earthquakes that affected Bangladesh caused a similar damage as shown in Table 1. Many researchers have studied the possibility of a similar earthquake occurrence and the damage that it would cause to today's Bangladesh. According to Sarker et al. study in 2010, a similar earthquake to the 1918 Srimangal earthquake would affect at least 10% of the city population directly (deaths and injuries). Old structures would be affected to the point that they cannot be used anymore, lifelines would take a huge damage and access to clean water would be difficult for months. In other words, the damage would be catastrophic and the city would take years to recover. The study concluded that public awareness about earthquake hazards should be raised and that there is a need to implement structural and nonstructural mitigation measures to reduce earthquake seismic risk (Sarker et al. 2010). In response to the public concerns and to cope up with the international advances in design principles, old Bangladesh National Building Code (BNBC 1993) laid the first stones for seismic design of structures. The code classified Bangladesh into three seismic zones; High hazard zone (East region), Moderate hazard zone (middle region) and low hazard zone (West region). A newer version of the code (BNBC 2017) includes sophisticated rules about designing structures to resist earthquakes and implementing modern seismic isolation systems. (BNBC 2017) classifies Bangladesh into five seismic zones with similar seismic zoning to older versions; higher levels to the East side of Bangladesh (Al-Hussaini and Chowdhury 2015), (Zakir, Akther, and Amanat 2019). Figure 1. (a) shows the seismic map of Bangladesh.

1.2 *New bridge projects in Bangladesh and Japanese Seismic Isolation systems*

With Bangladesh located in the middle of Asia, both Asian Highway Network and Trans-Asian Railway projects are expected to pass through Bangladesh's high seismic hazard region (East) as shown in Figure 1. (b), (c). That being said, the bridges that will be constructed as a part of both networks would need to be designed and constructed to resist earthquake loads. Japan has a very long history of earthquake events due to its location in the intersection of tectonic plates. Structures behavior due to earthquakes has been studied extensively over the years by Japanese engineers and scientists. Mitigation devices and techniques were developed and proved effective during real earthquakes. That is why Japanese seismic isolation systems are often considered the most reliable systems in the world. The principles of seismic design and characteristics of devices developed by Japanese companies that were used in Bangladesh will be discussed in the next sections.



(a) (b) (c)

Figure 1. (a) Seismic map of Bangladesh and (b) Asian Highway Routes; and (c) Trans-Asian Railway Network in Bangladesh (ASC, India 2006), (United Nations-ESCAP 1999), (Khandaker 2011)

Table 1. List of Strong Earthquakes that affected Bangladesh

Date	Name of Earthquake	Magnitude Mw	Epicenter
8 July 1918	Srimangal earthquake	7.3	Bangladesh-Tripura border
21 November 1997	Bandarban earthquake	6.1	Mizoram, India
25 April 2015	Nepal earthquake	7.8	Ghyachok, Nepal
13 April 2016	Myanmar earthquake	6.9	Mingin, Myanmar
3 January 2017	Tripura earthquake	5.7	Tripura, India

2 DEVICES FOR BRIDGES: HIGH DAMPING RUBBER ISOLATORS

2.1 *Seismic isolation principles*

When thinking about the behavior of a structure during an earthquake, three structural characteristics control how a structure behaves: ductility, energy absorption and strength capacity. In the past, strength was considered the most important characteristic to resist an earthquake. Therefore, stronger, bigger structural elements were considered to have better seismic performance. However, producing large elements would result in a problem with budgeting. Due to economic reasons, the strong structural element idea was replaced gradually to the idea of creating a structure that would be flexible to resist earthquakes without suffering significant damage. That is when the energy absorption characteristic became important. The lateral energy absorption capacity of a structure can be improved by many methods; for example, creating sacrificial plastic hinges that would absorb the transmitted energy from the earthquake. Another idea is adding flexible elements to supporting locations (column base, column cap or pier) to absorb the lateral energy. The idea is similar to how springs in a suspension system of a car work when it goes above bumps; the suspension system is responsible for absorbing the energy and making the passenger feel comfortable by reducing vibration. Similarly and by adding rubber to the base of a structure, the energy transmitted to the structural elements decreases and the forced vibration due to the external excitation (earthquake) is damped and absorbed by the isolation system as shown in Figure 2. It should be noted that when thinking of the car suspension system, the vibration is usually called a free vibration where there is no external excitation source. On the other hand and for the earthquake, the vibration is called a forced vibration where the excitation force resulted from the earthquake is a part of the equilibrium equation for the system as shown in Figure 2. Rubber material, known to have higher deformability than concrete or steel, absorbs most of the energy. Therefore, the structural elements are expected to be smaller and economic when rubber bearings are considered in the design stage of a structure. Rubber bearing behavior for lateral loading is usually simplified to a bilinear relationship between force and displacement. Several modeling strategies have been developed to describe the highly nonlinear behavior of rubber seismic isolators (Amin et al. 2014). The most commonly used model is the bilinear model as in Figure 3. The figure shows the absorption capacity of rubber bearing and its simplified form. The area of the hysteresis curve represents the energy absorption capacity of the rubber bearing. Figure 3. (a) shows the initial loading behavior of the rubber (K_1) until the yield point when the behavior changes and the slope inclination is lowered to (K_2).

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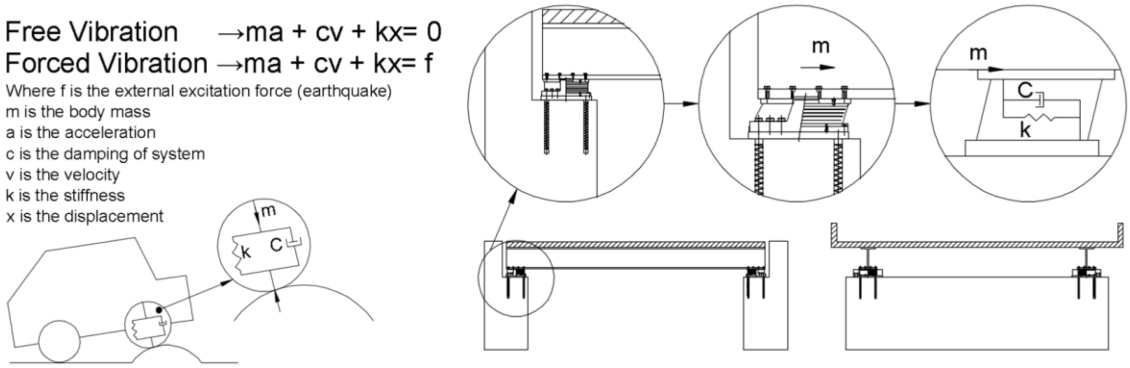
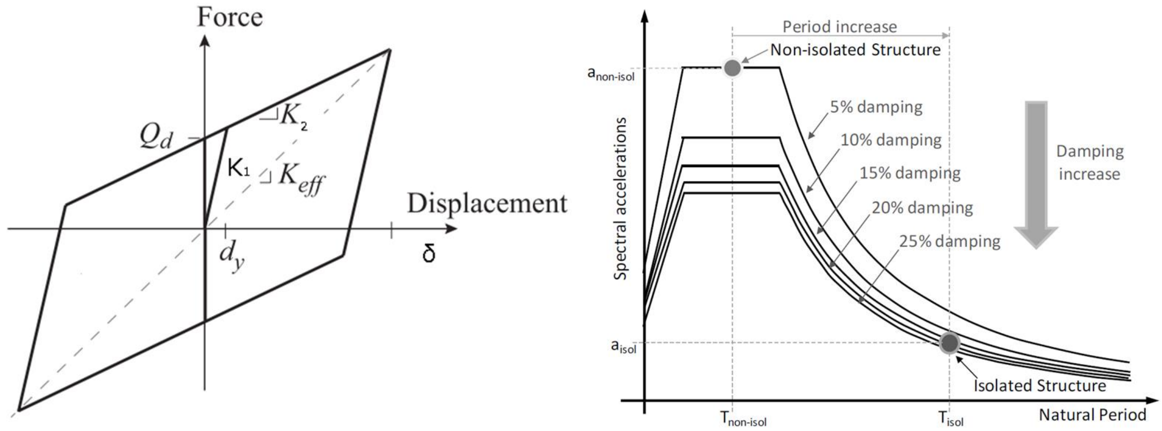
Figure 3. (b) shows acceleration response spectra for different levels of energy absorption. It can be concluded that by increasing damping, it can be expected that the seismic accelerations would be reduced. In other words, energy would be absorbed by the isolation system and would not be transmitted to structural elements. Energy absorption capacity depends on many factors including structure natural period, soil type and isolator properties (Lopez Gimenez et al. 2018).



(a) (b)

Figure 2. Simplified single degree of freedom vibration system of (a) Car suspension system; (b) Bridge isolation system

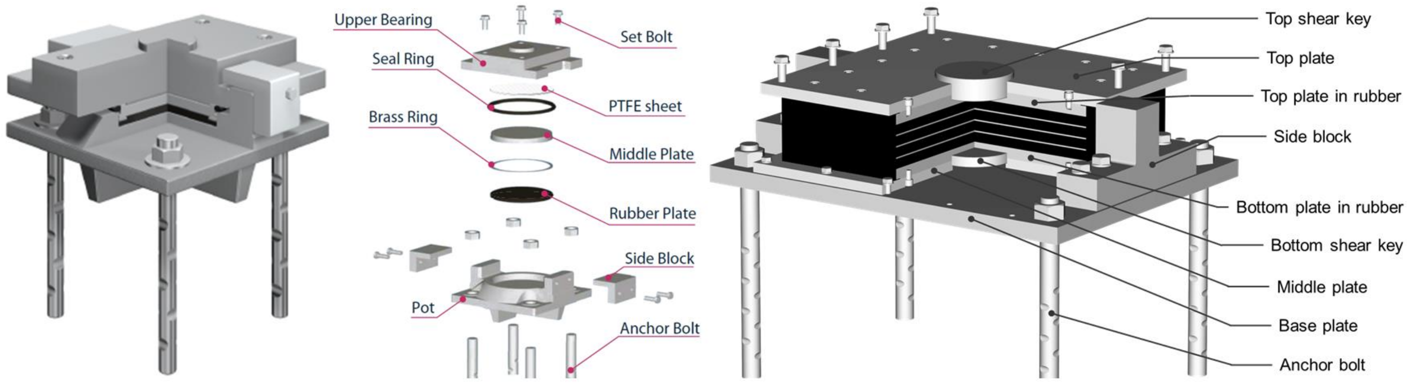


(a) (b)

Figure 3. (a) Bilinear horizontal force-displacement curve of rubber bearing; (b) Acceleration response spectra of different systems showing damping and reduction of seismic acceleration

2.2 *Types of seismic isolators for bridges*

A bridge bearing is a structural component typically located between the bridge pier (substructure) and girder or deck (superstructure). The main purpose of the bridge bearing is to transfer the loads from the substructure to the super structure. The main loads transferred by the bridge bearing are the vertical loads due to dead and live loads and horizontal (lateral) loads due to wind, earthquake, temperature and breaking. Some of the bearing are fixed and some other types allows lateral movement (in longitudinal and transverse direction) and rotational movement. A proper bridge bearing should be designed to transfer all the design loads, allow or restrain movement as per design requirements and keep its functionality for an adequate period. Bearings of bridges can be classified into steel and rubber bearings. Steel bearings accommodates the translation, rotation demand by mechanical movement while rubber bearings accommodates it through the deformation of the rubber. Rubber bearings are known to be cheap and practical and have a higher energy absorption capacity. They have been widely used in Japan following the Great Hanshin earthquake in 1995. The earthquake showed that bridges are vulnerable to earthquake risks. Engineers and scientists started to think more about how to reduce the effect of earthquake on structural elements and they found that using rubber bearing would improve the seismic performance of bridges. Steel bearings are usually selected for railway and metro projects due to vibration and strict rules controlling allowable vertical deformation. Steel bearings have better performance when rotational deformations are large at girder end supports. One example of steel bearing is the pot bearing shown in Figure 4 (a). Pot bearing is composed of upper and lower steel plates, internal PTFE sheet, middle plate, brass ring and rubber (or brass) plate. On the other hand, rubber bearings are a more economical solution than steel bearings for simple girders bridges. The elastomeric bearings shown in Figure 4 (b) are made by placing rubber and steel shims in a mold then increasing temperature and pressure to vulcanize the rubber and help to improve the interlayers bond. Usually, a rubber cover is attached to the outer side of the rubber after vulcanization to add more protection to the bearing against environmental conditions. Rubber can be classified into two main groups: low damping rubber; and high damping rubber (Warn and Ryan 2012). Due to the high intensity of earthquakes in Japan, side blocks, anchor bolts (and anchor bars) are added to the bearing to prevent the detachment due to strong earthquakes. Choosing a seismic isolator depends on the type of structure, lateral movement and energy absorption capacity, supporting condition, vertical reaction force and location.



(a) (b)

Figure 4. (a) Structure of steel pot bearing (BPB); and (b) Structure of High Damping Rubber Bearing (HDR-S)

3 APPLICATION OF HIGH DAMPING RUBBER BEARING TO PROJECTS IN BANGLADESH

3.1 *Kanchpur, Meghna and Gumti 2nd Bridges Construction and Existing Bridges Rehabilitation Project*

Due to the GDP growth rate of Bangladesh in recent years, Dhaka-Chittagong National Highway No.1 has become an important part of the nation's network. That required a rethinking process about the efficiency of roads and bridge along the highway. The government has been working on the improvement and widening of all the sections of the highway except for the parts crossing the Kanchpur, Meghna and Gumti Bridges (originally constructed in 1977, 1991 and 1995, respectively), which caused traffic jams on them (Hasan and Roksana 2019). Also, the three bridges have been under severe damage due to the heavy vehicles that pass on them every day with a load exceeding its design capacity and the inappropriate maintenance (JICA 2013). JICA has undertaken a feasibility study on the construction and rehabilitation of the existing bridges (shown in Figure 5 ((IHI Corporation 2015).

The study concluded that the construction of new bridges as well as repairing and rehabilitation of existing bridges are crucial to help the economy keep the same economic growth rate. Other studies highlighted the importance of these bridges and the need of providing high-end technologies to ensure the serviceability of the bridges even in a strong earthquake (Saidul Hoque et al. 2015).

3.1.1 *Damage to structural elements, hinges, expansion joints and bearings of the three bridges*

Due to the previously mentioned reasons, a study on the damage level of the three bridges was conducted. It was found that the three existing bridges should be retrofitted to endure larger design loads than its original design capacity (from the original AASHTO HS20-44 ASD to a combination of the newer AASHTO LRFD, HS20-44 and Japanese standards).

The studies emphasized the changes in design codes regarding the earthquake design and recommended carrying out measures to prevent the bridges from collapsing during earthquakes. The measures recommended including adding steel brackets to the substructures at the girder ends, connecting girders ends at the halving joint of Kanchpur Bridge and implementation of additional pedestals and fail-safe connection to prevent girders' falling of pedestals. Regarding the structural elements, it was found that cracks and water leakage were found in the sub-structure of three bridges while some of the girders, crossbeams, and deck slab had no or minor cracks with some rebar exposures. According to the studies, the hinges lost their proper function to transmit shearing forces at the connection between girder and pier (and abutments), causing noise and impact forces that affected expansion joints' performance. The expansion joints also had a severely deteriorated condition because of the previously mentioned impact forces. The results of the study concluded that there is a need to replace the types of hinges and expansion joints of the three bridges.

3.1.2 *The new Meghna Bridge and repair of the existing Meghna Bridge*

The existing Meghna Bridge is a two-lane, 13 spans (9 PC box + 2 PC-T girder) bridge, having all expansion joints at the mid of each span, with a total length of 930 m. The expansion joints were replaced and some of

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the hinges were fixed by filling concrete in the embedded space and placing PC cables, while some other hinges were replaced. Some of the pot bearings at the center were replaced by new bearings. A new bridge of 12 spans with the same length as the existing bridge and located at its side was constructed as shown in Figure 6. The new bridge consists of three continuous narrow box steel girders monolithically joined with a steel-concrete composite slab. Expansion joints were provided at both ends of the bridge (Tatsumi, Ghosh, and Ohtake 2015).

(a) (b) Kanchpur Bridge

(c) Gumti Bridge (d) Meghna Bridge

Figure 5. (a) Location of the new construction and rehabilitation projects; (b) Kanchpur, (c) Gumti, and (d) Meghna Bridges (IHI Corporation 2015)

In the planning phase of the project, it was clear that using rubber bearings between substructures and super-structures was the most adequate supporting condition for this continuous girder bridge. This support configu-ration allows an even distribution of horizontal forces among the different piers and avoids detrimental con-centration in a single substructure. Addition of damping mechanism to the structure with the installation of HDR-S was evaluated in order to reduce the seismic demands in the structural members (Lopez Gimenez et al. 2018). 117 HDR-S bearing were provided for the three bridges projects with different sizes and capacities as shown in
Table 2.

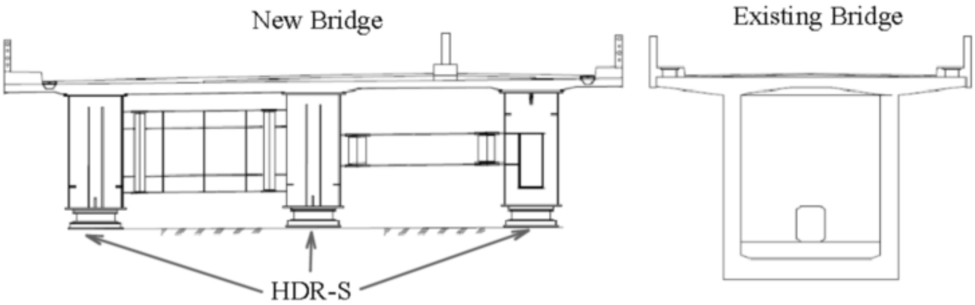

Figure 6. 2nd Meghna Bridge and existing Meghna Bridge

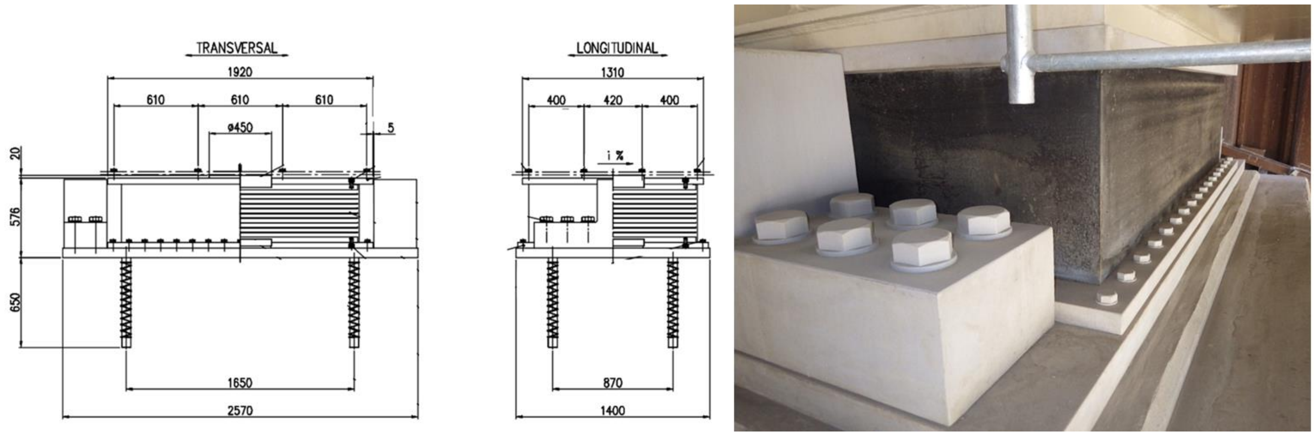

Figure 7. HDR-S used for the new construction of the 2nd Meghna Bridge

Table 2. Delivery list of HDR-S bearing to the new Kanchpur, Meghna and Gumti Bridges

Bridge	Set	Rubber body size (mm)	Maximum Reaction Load (kN)
Kanchpur	6	1070 x 1070 x 233	2700
	3	1070 x 1070 x 200	8600
	6	970 x 970 x 213	11500
	3	970 x 970 x 175	7450
	3	1070 x 1070 x 200	6650
Meghna	6	1070 x 1720 x 421	3350
	12	1470 x l470 x 398	10700
	9	1220 x l220 x 296	10750
	9	970 x 970 x 243	10450
	3	1220 x l220 x 296	10300
Gumti	6	1120 x l220 x 337	2950
	6	1220 x l220 x 353	9750
	6	920 x 920 x 311	11000
	24	920 x 920 x 291	11000
	6	1220 x 1220 x 357	12000
	6	1270 x 1270 x 360	5100
	3	920 x 920 x 30l	10700
Total	117		

4 DURABILITY OF RUBBER BEARING AND IMPORTANCE OF LONG-LASTING RUBBER

Because of the high initial cost of construction compared to maintenance (in the short term), engineers usually ignore the importance of frequent checks and repair works needed for the structure to keep its functionality for the designated life span. Bearings and expansion joints are usually thought of as unimportant parts of the bridge structure or as accessories, but in fact, bearings and expansion joint conditions control how the whole bridge behaves during daily loading conditions and earthquakes. In daily traffic conditions, deteriorated bearings would lead to damage to bridge elements (girders, piers or both). Damage to the expansion joint due to maintenance problems or design inadequacy can lead to discomfort of road users, partial or full closure of the road and serious accidents. Bearings are thought to be elements that should have a minimum maintenance cost, engineers expect it to keep its conditions for many years before they are exchanged. That is why the rubber bearings have gone through many development processes and the rubber characteristics were improved to meet the long life span expectations.

Rubber bearing is strong against corrosion as rubber acts as a shield that protects the internal steel shims against deterioration. However, the presence of ozone in the atmosphere can decrease the durability of poorly engineered rubber compounds and rubber bearings with low quality. In recent years, crack damage (ozone crack) due to ozone has occurred in rubber bearings due to use under severe conditions. If the damage is left untreated, the damage spreading is expected. As a countermeasure, methods were developed to suppress the crack growth by coating rubber.

To guarantee a long life span and performance, many tests on rubber material are required.

In the next subsections, ozone cracking is explained, tests on rubber, which was treated using different protection methods, will be discussed, and the test findings on rubber will be explained.

4.1 *Ozone cracking resistance of Bearings and its performance*

Ozone can destroy the double bonds of the carbon atoms of rubber and thus, make the rubber weaker. As a result, microscopic cracks appear on the surface. Accompanied with the ozone cracks, rubber bearings constantly undergo changes in shear deformation due to expansion and contraction caused by temperature changes of the girders. The continuous movement of the bridge can widen the ozone cracks, which directly affects the durability of the rubber bearing. Therefore, a coating material that has both weather resistance and the ability to follow the shear deformation of rubber bearings is required.

Due to the harsh environmental conditions of Bangladesh, it is important to pay special attention to the quality of the rubber material used in bearings and use protective coatings to increase the protection against ozone attack. In addition, existing rubber bearings with low ozone resistance should be protected to prevent its deterioration and extend its life expectancy.

One example of protective coatings is to use elastic coatings that act as a barrier to prevent ozone to get in contact with the rubber surface, while maintaining the elasticity of the rubber bearing, and one of these elastic coatings is the K-Coat-R.

K-Coat-R has proven to have excellent weather resistance ability (ozone resistance) while keeping good structural performance. K-Coat-R can be applied to new and existing bearings, which extends the lifespan of the bearing. According to the quality assurance tests, specimens treated using K-Coat-R was 10 times stronger than the required resistance as per standards. It has also shown the ability to accommodate 300% shear strain against shear deformation of bearing. The three main factors that define the quality of rubber coating are how it is useful to resist environmental conditions and weather, how it affects the shear loading performance of the rubber bearing and whether it is easy to be applied to new and existing rubber bearing (workability). All the three factors are verified by the tests and the results are discussed in the next subsection.

4.2 *Tests on rubber bearings for ozone crack resistance*

Performing ozone-accelerated tests, where ozone of high concentration is used, is a common procedure to develop resistant rubber compounds against ozone attack. The tests only take few weeks and can indicate the behavior of the rubber during service life. To test the behavior of rubber material, Dumbbell specimens (dog bone) are used for tension test (similar to coupon tests) while being under certain conditions to check the ozone resistance performance. The specimens are untreated uncoated rubber, silicon-coated rubber and K-Coat-R coated rubber. The stretch rate reaches up to 50%, and the specimens are tested at an Ozone concentration of 50 pphm and a temperature of 40℃.

The results showed that within the first 24 hours, cracks started to appear on the entire untreated surface of the specimen with no coating layers. For the specimen with silicon coating, cracks started to appear after 264 hours. For the K-Coat-R coated specimen, cracks did not appear even after 1000 hours of testing.

K-Coat-R has also proved to be effective with different rubber material types (Natural rubber (NR) and Chloroprene Rubber (CR). Other experiments were carried out to verify the performance of K-Coat-R and when compared to silicon coat, the performance was significantly better. Figure 8 shows the specimen shape, testing machine and different experiments setting on rubber. Figure 9 shows a real example of using K-Coat-R for the treatment of an existing bearing. The treated bearing did not show cracks for 5 years after treatment.

(a) (b) (c)

Figure 8. (a) Testing dumbbell specimen and (b) Ozone resistance-testing machine and (c) difference between coatings.

(a) Ozone cracks appearing on a poor quality rubber bearing (b) Bearing after 5 years of treatment using K-Coat-R

Figure 9. Ozone cracks and treatment of existing bearing using K-Coat-R

5 CONCLUSION

Kanchpur, Meghna and Gumti 2nd Bridges Construction and Existing Bridges Rehabilitation Project is a very important step for Bangladesh. It will directly provide more opportunities to local people, as it will facilitate movements between cities, allowing easy movement between different parts of Bangladesh and South Asia. The rehabilitation process was done smoothly and structural performance and safety of existing bridges were improved.

The new bridges project will improve the traffic flow along the N1 Highway. They were designed to accommodate earthquake loads, which mean that they will be able to stay function even after an earthquake occurrence. New techniques for treatment of bearings can enable it to accommodate severe structural loading and environmental conditions. A rubber bearing where K-Coat-R was used has proven good performance in resisting rubber ozone cracking and steel corrosion. Using protecting techniques for new and existing bearings will reduce the maintenance cost and will improve the performance of the bridges and save money in the future.

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