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# Some Considerations in the Design of Natural Rubber Bearings for the Penang Bridge

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*Natural rubber bearings have gained widespread application in reinforced concrete and in prestressed concrete bridges[1]. They were installed in the Penang Bridge Project. Certain important findings in regard to the durability and fatigue life of NR for bridge bearings are reviewed in relation to the requirements of the site of the Penang Bridge.*

*In good design, rubber is normally not used in tension. To ensure that no point in the rubber bearing is subjected to an upward movement and results in hydrostatic tension, rotations are limited by BE 1/76[2] in accordance to which the NR bearings for the Penang Bridge Project were designed.*

*The most likely stage in which the rubber may be subjected to tensile stresses is in the early period of the construction when the precast prestressed concrete beam is first installed on the top of the supporting bearings. Compressive load-deflection test results of some of the installed bearings are presented. On the basis of these test results and together with the actual deflections of a precast prestressed concrete beam measured at the site, a computation is presented to verify that at no stage in its service life the rubber bearing concerned will be subjected to tensile stress.*

Rubber bearings for reinforced and prestressed concrete bridges have gained increasingly widespread use since they were first introduced some three-and-a-half decades ago. They have no mechanical moving parts and do not present corrosion and wearing problems as the traditional steel roller and plate bearings; they are virtually maintenance-free and cost much less than mechanical bearings. Laminated rubber bearings allow not only movement in any horizontal direction but also rotation about any horizontal axis. This flexibility is important for modern bridges where thermal expansion of a wide orthotropic bridge deck does not always result in equal horizontal movements or equal rotations at the ends of every one of the many beams. In regard to noise absorption and vibration isolation, rubber bearings are far superior.

It is not surprising that rubber bearings are now replacing steel bearings. The suspension chain saddles of the Hammersmith Bridge across the River Thames were originally mounted on large diameter steel rollers. About fourteen years ago the bridge was upgraded and the seized steel bearings were replaced with 1.5 m long smaller diameter units. In February 1984, a combination of forces on the bridge made the steel rollers move further than anticipated on their bearing plates and eventually right off their ends. As a result, the deck slumped 60 mm. A computer simulation of the lateral and longitudinal loads indicated that rubber bearings would be most suitable and Hammersmith Bridge was put back into service with the saddles now mounted on permanent rubber bearings[3].

The construction industry in Malaysia is in a special position to take advantage of rubber bearing technology as Malaysia is the world's largest producer of natural rubber and has the technological back-up services of the laboratories and the Technology Centre of the Rubber Research Institute of Malaysia.

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Except at the navigation channel, all the spans of the Penang Bridge Project consist of precast prestressed concrete beams resting on cross-beams using natural rubber bearings. The prestressed concrete beams for the 40 m spans over the sea were designed as simply supported for dead load and continuous over five spans for live load.

Altogether 8846 NR bearings were installed in this project which has 13.5 km of bridging of which 8.4 km are over the sea. The largest bearings were designed for a vertical compressive dead load of 800 kN and for a live load of 400 kN.

The NR bearings were designed in accordance with BE 1/76 the fore-runner of which is UK Ministry of Transport Memorandum No. 802/1962[4] entitled 'Provisional Rules for the Use of Rubber Bearings in Highway Bridges,' both of which are based on the developmental work at the Malaysian Rubber Producers' Research Association. The Rubber Research Institute of Malaysia assisted in the design of NR bearings for the Penang Bridge in accordance with BE 1/76.

## DURABILITY OF NATURAL RUBBER BEARINGS

Extensive research on the durability and fatigue life of natural rubber for bridge bearings has been carried out by the Malaysian Rubber Producers' Research Association. Their findings are reviewed here in relation to the requirements of bearings for the Penang Bridge.

### Deterioration Due to Environmental Factors

*Low temperatures.* Most rubbers stiffen at low temperatures. Natural rubber does so less than most materials. It is therefore the preferred material under conditions of low temperatures. In any case temperatures low enough for such crystallisation do not occur at the site of the Penang Bridge.

*Oxidation.* There is evidence that rubber can survive very long periods in service at ambient temperatures of at least 30°C with no serious deterioration at all. Rubber bearings installed under prestressed concrete beams are sheltered from the direct sun and being in the shade, temperatures high enough for significant age hardening are not likely to occur.

Oxidation and attack by ozone as a result of long exposure to the atmosphere will only affect a relatively thin layer of rubber and this oxidation will thus be no more than a surface effect for bridge rubber bearings. The reasons for the oxidation to be so limited are: the diffusion of oxygen through oxidised rubber is much slower than through new rubber[5,6]; the diffusion of oxygen into rubber is a very slow process; and the extremely low rate of diffusion is further retarded by virtue of the rubber block being under compression. As in the oxidation of aluminium, the oxidised material forms a thin protective layer on the surface. However, rubber can be protected from oxidation and ozone attack by the incorporation of anti-oxidants and antiozonants.

The degradation of the natural rubber pads installed in an Australian railway viaduct completed in 1891 and recently examined, was found to be only superficial. Most of the cracks were less than 0.7 mm deep and below a depth of about 1.5 mm there was no visible evidence of deterioration[7].

*Sea water.* Rubber does not appear to be adversely affected by water. The absorption of water by rubber is very small[8,9]. The diffusion coefficient and solubility of water in rubber[10] are very small being $1.4 \times 10^{-6}$ cm$^2$ s$^{-1}$ and $3.3 \times 10^{-4}$ g cm$^{-3}$ respectively. The concern of the effect of water is not so much on the rubber itself but on the rubber-to-metal bonds. The effect of water on rubber-to-metal bonds has been shown to be not important even under conditions where the water has direct access to the bonds *i.e.* the edges of the metal is not covered with rubber[11]. However, the bearings for the Penang Bridge are located at least 6 m above the sea and are therefore not in direct contact with sea water.

### Time-dependent Crack Growth

Under static as well as cyclic load conditions, crack growth can develop in some rubbers.

Natural rubber is not normally prone to crack growth under static loads because of its ability to strain crystallise[12]. The formation of crystallites at the tip of a crack, where the high concentration of strain occurs, prevents further growth of cracks.

### Crack Growth

The tearing energy[13], which is the energy required to cause unit area of new crack growth, is a function of crack length in tension. In shear and in compression, the growth of a crack will not accelerate except at very small crack length[14]. This is however not the case in direct tension. Consequently in good design, rubber is not normally used in tension but only in shear and in compression under service conditions.

A prestressed concrete beam hoggs up on transfer of the prestressing force. As a result, the previously horizontal plane of the underside of the beam assumes a parabolic profile. The ends of the beam are no longer horizontal but are inclined at an angle to the horizontal plane. The situation in which rubber in a laminated bridge bearing is most likely to be in tension is when the bearing has to rotate to accommodate the inclination of the ends of a prestressed concrete beam. Tension of laminated bearings can result in internal cracks due to hydrostatic tensions.

### Compression Stiffness of Rubber Bearing

The direct compression of a laminated rubber bearing will depend on:

- the physical properties of the rubber after the bearing is manufactured
- the physical properties of the mild steel used for plate reinforcement
- the number and dimensions of the rubber laminates and mild steel plates.

At the design stage it is difficult to estimate the magnitude of the direct compression or deformation of a rubber bearing under a given compressive force. At best a minimum compressive stiffness based on past experience is

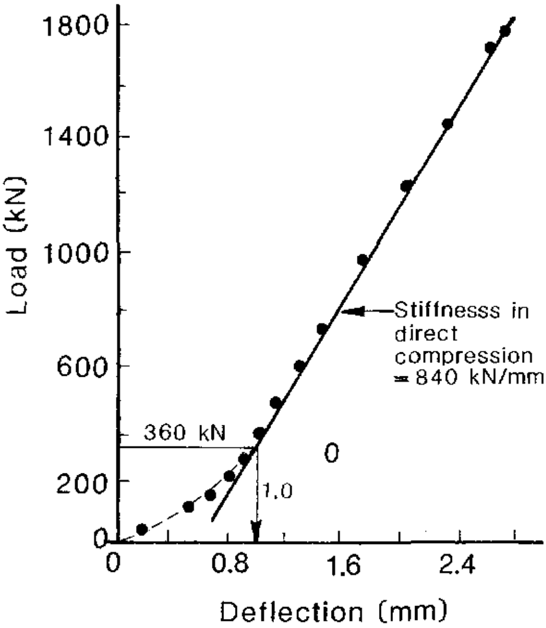


*Figure 1. Type 1 bearings: the relation between load and deflection.*

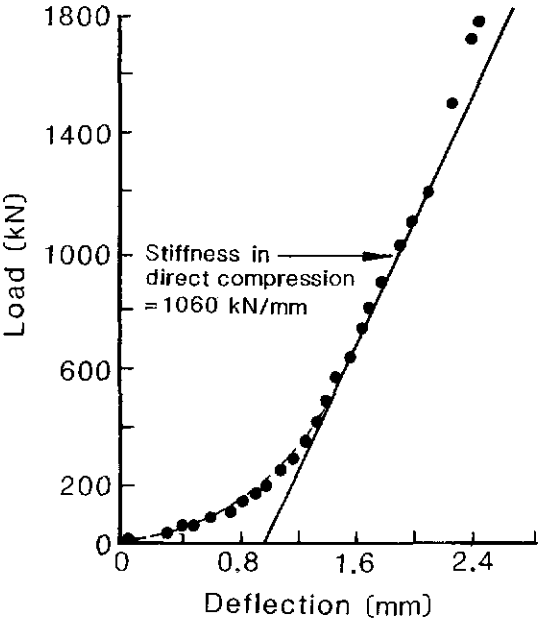


*Figure 2. Type 2 bearings: the relation between load and deflection.*

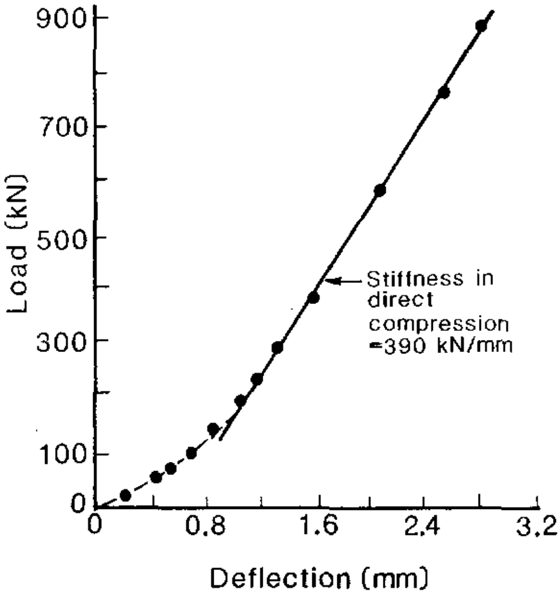


*Figure 3. Type 3 bearings: the relation between load and deflection.*

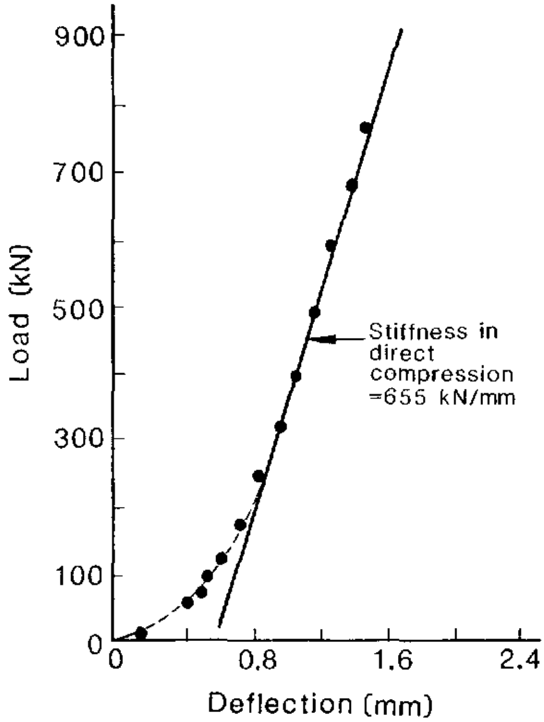


*Figure 4. Type 4 bearing: the relation between load and deflection.*

specified and the structural analysis of the orthotropic bridge deck is then carried out on the basis of this value.

For all the types of bearings for the Penang Bridge, a stiffness in direct compression of not less than 210 kN per millimetre and a stiffness in shear of not greater than 2.6 kN per millimetre were specified.

*Figures 1, 2, 3* and *4* give the load-deflection behaviour of some of the rubber bearings tested. In general, the load-deflection relationship begins to be linear only after a certain initial load. At loads less than this initial value the load-deflection relation is non-linear. At load values lower than this initial value the load per unit deflection is much lower. Consequently it is advantageous to design a bearing such that at no stage in the loading history the compressive force will fall below the linear part of the load-deflection curve.

All the four tests show that when the relation between compressive load and deflection becomes linear, the stiffness of the bearings in direct compression is greater than the specified value of 210 kN per millimetre.

**No Tension Assessment**

At the early stage of the construction when the prestressed concrete beam is placed on the top of a rubber bearing at each end of the beam, the direct compressive stress on the bearing is only that due to the weight of the beam itself. The inclination of the ends of the beam to the horizontal on the other hand, is the greatest. Because of the low direct compression and the highest angle of inclination of the ends of the beam, this is the stage at which the rubber is most likely if ever to be in tension. Under a normal programme of construction this situation prevails for only a short period. With the placement of the diaphragms and deck, their weights not only increase the direct compressive stress on the

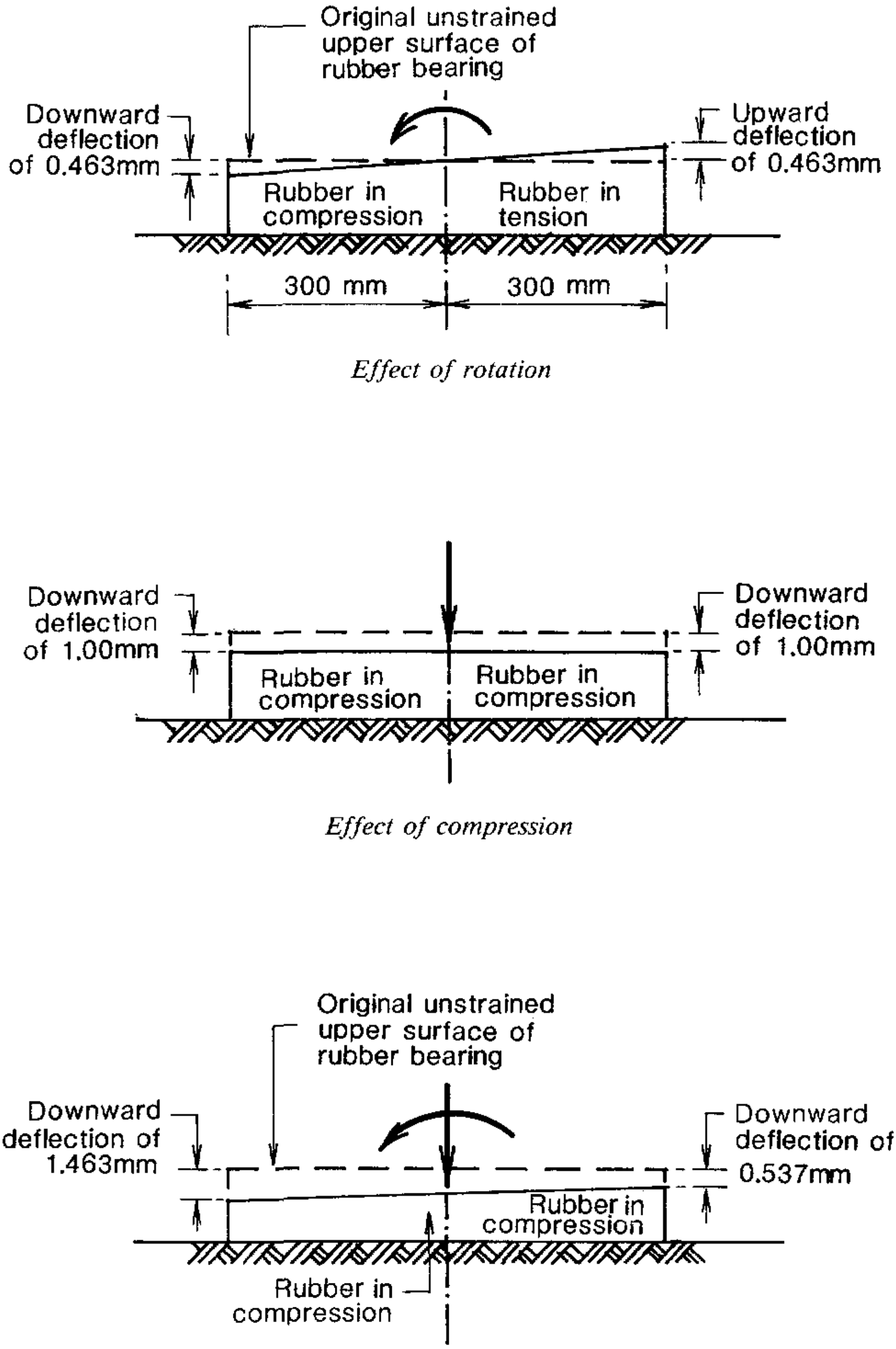


*Figure 5. Type 1 bearing: the combined effect of highest angle of rotation and lowest compressive load.*

bearings but also reduce the inclination of the ends of the beam to the horizontal. The subsequent live load, *i.e.* the traffic load further increases the magnitude of the direct compressive stress on the rubber bearings and further decreases the inclination of the ends of the beam to the horizontal. Consequently the stage at which rubber in the bearings is most likely to be in tension is at the early stage of the bridge construction when the rubber bearings support only the weight of the prestressed concrete beam. At this stage the hogging or upward deflection of the prestressed concrete beam is the net result of the upward deflection due to the prestressing force in the prestressing cables and the downward deflection of the beam due to its own weight.

At the design stage, it is difficult to determine the actual magnitude of the hogging because the magnitude of the elastic modulus of the concrete is not known. This modulus is mainly dependent on the crushing strength of the concrete but is however, influenced by the elastic properties of the aggregates, the conditions of curing, the age of the concrete, the mix proportions and by the type of cement used. Approximate values are given in CP 110 (British Standard Code of Practice for the structural use of concrete) but if an accurate figure is required, the best method is still to measure the deflections on the actual beams under loads. However, this can only be done during the construction stage.

During the manufacture of the prestressed concrete beams in the Penang Bridge Project, the hogging at the centre of each beam at transfer of the prestressing force was also measured. Analysis of the measured results of sixty-five beams of length 39.820 m each subjected to the same total prestress force of 8004 kN showed that the average net upward deflection at the centre of the span due to the combined effect of the prestress and of the beam's weight, was 30.75 mm. At the ends of the beam the average slope of the underside was therefore 1 vertical to 647.5 horizontal. The length of the rubber bearing *(Type 1)* is 600 mm in the direction of the longitudinal axis of the prestressed concrete beam. Consequently the rotation of the bearing to accommodate this angle resulted in an upward rise of 0.463 mm on the tension edge of the bearing and an equal downward deformation on the compressive edge.

The weight of the prestressed concrete beam exerts a direct compressive force of 360 kN on the bearing. This results in a downward deformation of 1.00 mm over the whole bearing. The combined effect of the rotation and direct compression is that every part of the bearing is under compression *(Figure 5)*.

ACKNOWLEDGEMENT

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