Uplift bearings – selection and design considerations

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ABSTRACT: The vertical forces exerted by bridge decks and other structures on their supports are not always downwards; uplift can occur for a variety of reasons. Upward forces are generally transient, lasting no longer, for example, than the duration of a strong wind or of live loading of the relevant section of the structure. Although the structure's bearings must typically still be capable of carrying downward forces, facilitating rotations, and resisting horizontal forces and/or accommodating displacements, they must now be able to do all of this even under uplift conditions. And if the frequency of load reversal is high, then the uplift load condition may become fatigue-relevant, adding yet another dimension to the design - especially if the load reversals would cause hammering of interfaces such as the sliding surfaces of a sliding bearing. This paper describes key issues which must be considered in selecting and designing bearings for uplift conditions.

1 INTRODUCTION

A structure's bearings play a critical role in its proper functioning and performance, typically accommodating movements and rotations while carrying loads and resisting other forces. In doing this, they generally enable the structure to function far more efficiently than it would in the absence of bearings, allowing bending moments and stresses to dissipate in a controlled manner.

Most bridges require their bearings to resist downward forces, with resultant upward forces never arising. If no horizontal forces must be resisted, the basic design of the bearing may be relatively simple, as shown in Figure 1 for the case of a spherical bearing. If horizontal forces are to be resisted (in the longitudinal or transverse direction, or both), this can generally be achieved by the addition of stops or guide bars, for example as shown in Figure 2.

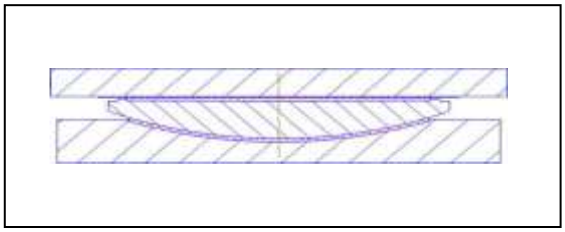
Figure 1. Cross-section of a typical spherical bearing (free sliding type), which must not resist uplift forces

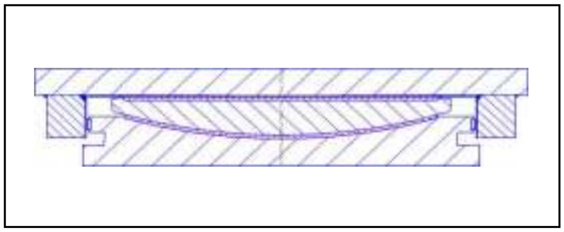
Figure 2. Cross-section of a typical spherical bearing (guided sliding type, with guide bars on sides allowing horizontal sliding movements)

However, the design becomes significantly more complicated if any type of uplift force must be considered, as described below.

2 DESIGNING BEARINGS FOR UPLIFT FORCES – KEY CONSIDERATIONS

Uplift conditions can arise for a variety of reasons, including

- wind, especially on roofs and light, narrow structures such as pedestrian bridges,
- vibrations and significant dynamic forces, such as may arise on a railway bridge,
- vertical ground acceleration (especially at near-fault locations) during earthquakes, and
- live loading, on a structure with a sensitively balanced design.

The frequency at which such uplift conditions occur is of considerable significance for the design of the bearings which must resist these forces. If uplift is expected to occur only rarely, then the uplift aspect of the bearing’s design may simply have to prevent upward movement on these rare occasions. However, if uplift conditions can occur frequently, the repeated load reversals may be fatigue relevant, and if they cause movements that can cause hammering (e.g. at sliding interfaces that can pull apart under uplift conditions), damage to materials can result.

The movements that must be accommodated by the bearing (if any) are also very significant. If the bearing has to accommodate horizontal movements, by deformation or sliding, the task of designing to resist uplift is more complicated. And if such movements are by sliding, then the sliding interfaces require special attention to prevent damage from hammering and contamination. Of course, all other demands on the bearing must also be given due consideration.

It must also be recognised that uplift conditions do not place demands on the structure’s bearing alone. The uplift forces must also be safely and reliably transmitted from the bearing to the connecting structures above and below, by means of suitably designed anchors in sufficiently strong structures. And these anchorages must not only resist direct uplift forces; they must also fully resist any horizontal forces that may arise, because friction cannot contribute in the absence of pressure. In general, where a certain minimum vertical force can be relied on to act whenever a horizontal force occurs, much or all of the horizontal force can be resisted by friction, reducing the need for anchoring. But if uplift can occur, this benefit is not available.

Verification of the adequacy of designs of uplift bearings is generally limited to design proofs, perhaps including testing of components or materials as appropriate. The European standard for bridge bearings, EN 1337, does not directly cover the design of uplift bearings (with European Technical Approvals arising for such cases), let alone how such bearings should be tested. Testing a bearing for uplift force is generally considered unnecessary where the uplift force is a constant, static force or if it will only occur in extreme circumstances (e.g. during a ULS case such as an earthquake), because the ability of a bearing to resist such forces can generally be adequately proven by calculations and testing of materials. And testing for uplift would be very costly if the uplift condition occurs frequently, with many load reversals, requiring a dynamic testing rig. An example of how testing was carried out for such a case, with testing limited to verifying the compressibility of bearing parts, is described in Section 5.1 below.

3 STANDARD UPLIFT BEARINGS – WITH EXTERNAL UPLIFT PROTECTION

As noted above, if uplift is expected to occur only rarely, then the uplift aspect of the bearing’s design may be relatively simple. The basic spherical bearing designs presented in Figures 1 and 2, for instance, may be adapted as shown in Figure 3, with uplift clamps at each side. These can be designed to also allow horizontal movements (longitudinal or, to a degree, transverse), or to prevent such movements, depending on the bridge’s requirements.

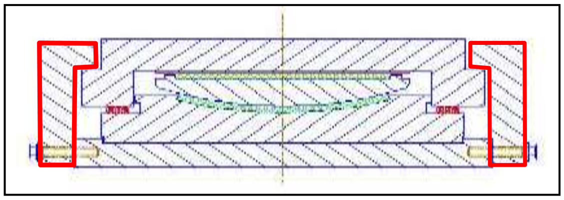

Figure 3. Cross-section of a spherical bearing with uplift clamps (outlined).

Examples of the use of bearings with such uplift-resisting capabilities are presented below.

3.1 *The uplift bearings of the Revere Beach Pedestrian Bridge, Massachusetts*

The new Christina and John Markey Memorial Pedestrian Bridge (Figure 4) opened in early 2013, providing access to America's oldest public beach from a subway station and a major new multi-level car park at the other side of a busy road.

Figure 4. The new Revere Beach pedestrian bridge.

Figure 5. The bearings required by the bridge's design – including two uplift bearings at front.

The structure requires two bearings at each end (Figure 5). At one end, which is designated the fixed end, the loads are resisted, and the deck is held in place, by spherical bearings. At the other end, which must be able to move longitudinally, the bearings are based on a sliding elastomeric bearing pad and a stainless steel sliding partner. These bearings are designed with uplift clamps to resist the significant 19 kip (84 kN) uplift force arising while facilitating longitudinal sliding movements. The uplift clamps of one bearing allow limited sliding in the transverse direction, making it a free sliding bearing (see Figures 6 and 7), while those of the other bearing resist transverse forces and movements, making it a guided sliding bearing (Figures 8 and 9).

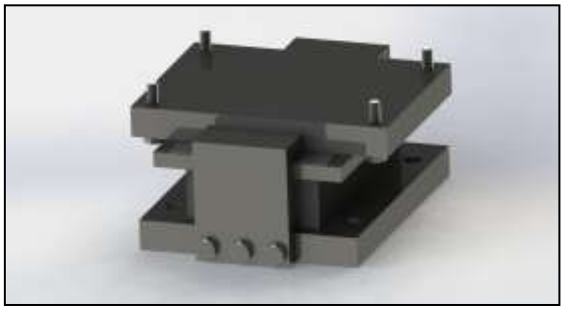

Figure 6. Design of the free sliding uplift bearing, with a reinforced elastomeric pad at its core. The uplift clamps (bolted) at each side resist uplift but allow limited transverse sliding movement.

Figure 7. Section through the free sliding uplift bearing. The elastomeric pad is held in place by keys in the steel plate at its base, and the bearing's upper plate can slide across its PTFE top surface.

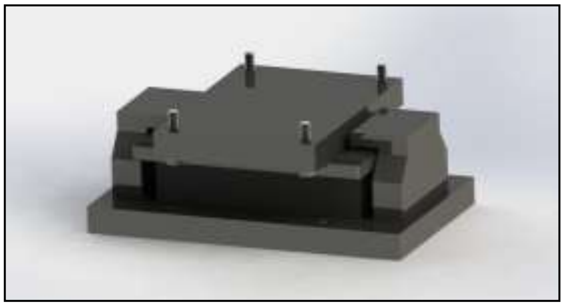

Figure 8. Design of the guided sliding uplift bearing. The uplift clamps (welded) at each side are designed to also resist transverse forces.

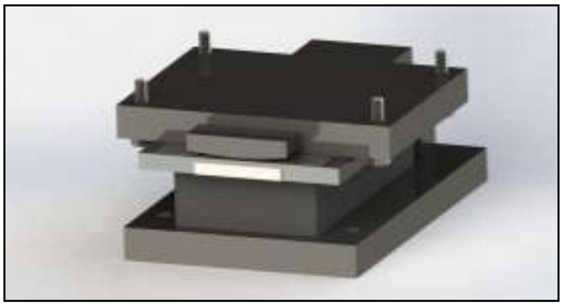

Figure 9. Section through the guided sliding uplift bearing, with the vertical plate of one uplift clamp removed. The horizontal upper part of the clamp is shown, with curved lower surface allowing rotations of the sliding plate it holds down.

3.2 *The uplift bearings of the roof of the Kimbell Art Museum, Fort Worth, Texas*

The Kimbell Art Museum in Fort Worth, Texas is a world-renowned building, and has won wide acclaim for its design since its opening in 1972. A second building (Figure 10), designed by world-renowned architect Renzo Piano, is scheduled to open in 2013 and will provide space for special exhibitions, allowing the original building to showcase the permanent collection. It will also accommodate dedicated educational spaces and an approximately 300-seat auditorium. The building design includes many striking features, including its roof, which spans gracefully above the large exhibit areas.

Figure 10. The Kimbell Art Museum, Fort Worth.

Figure 11. Packing of bearings for transport to site, showing compact size.

To enhance its aesthetic qualities, the architect specified that the 66 bearings which support the roof and allow its movements should be designed and positioned to be very discrete, and thus as small as possible (see Figure 11). Considering the horizontal and vertical forces (including uplift forces of approximately 75 kips (330 kN) to be resisted by the bearings, and the movements that they would have to accommodate, linear rocker bearings were proposed. The design of these is illustrated by the renderings in Figures 12 to 15.

Figure 12. Rendering of a fixed linear rocker bearing with uplift protection clamps at each side. The bearings feature anchor sockets for connection to a concrete support structure beneath.

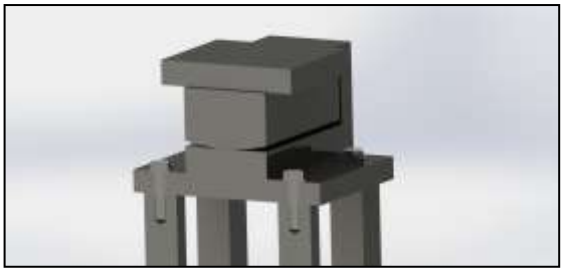

Figure 13. Section of bearing shown in Figure 12. The curved lower surface of the upper element has shear key connections to the plate below (as shown in Figure 15), allowing it to rotate but not to move.

Figure 14. Rendering of a guided sliding linear rocker bearing with uplift protection clamps at each side.

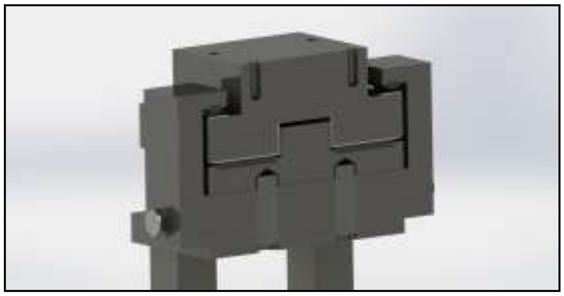

Figure 15. Section of bearing shown in Figure 14. The rocker element of the fixed bearing in Figures 12 and 13 is replaced by a two-part unit, the top part of which slides across the lower part, along one axis.

4 ADVANCED UPLIFT BEARINGS – WITH INTERNAL UPLIFT PROTECTION

In some cases, where loading conditions are demanding with frequent load reversals, bearings with external uplift clamps as described above may be at risk of fatigue failure due to the eccentricity of the uplift clamps. This eccentricity results in moment effects and prying action, which are demanding on the connections within the bearing. To overcome this, some types of bearing can be designed with internal uplift protection, with uplift forces (like the normal downward forces) flowing through the bearing's center. Figure 16 shows a spherical bearing with such a solution; the simple calotte of the bearing shown in Figure 3 has been replaced by a two-part mechanism, the upper part of which is bolted through the lower part to the concave element below.

The flow of forces through the bearing, under downward and uplift force conditions respectively, is illustrated in Figures 17 and 18. As can be seen from Figure 18, uplift forces are directed through the bearing's center, resulting in only minimal eccentricity.

A current example of the use of such a design is presented below.

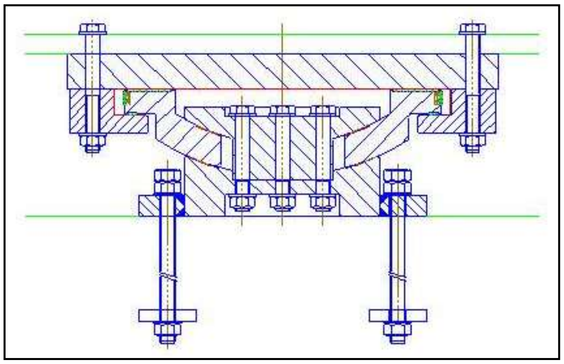

Figure 16. Cross-section of a spherical bearing with internal uplift protection – avoiding eccentricity of forces and reducing the effects of loading.

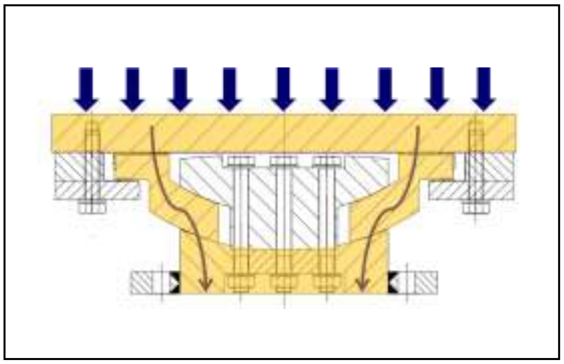

Figure 17. The flow of downward forces through the bearing shown in Figure 16.

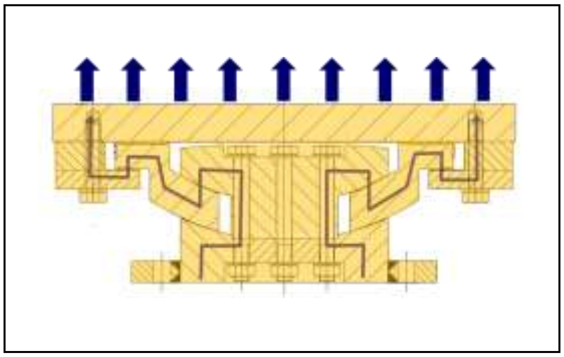

Figure 18. The flow of uplift forces through the bearing shown in Figure 16.

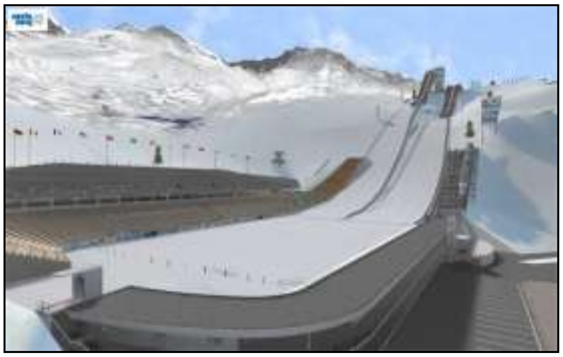

Figure 19. The new ski jump facility at Sochi.

4.1 *The uplift bearings of the landing area of the Sochi Ski Ramp*

The all-season resort city of Sochi on the north-eastern shores of the Black Sea is currently being prepared to host the 2014 Winter Olympics. For the engineers who must design and construct the extensive new facilities, the project has presented many challenges, such as the high seismicity of the area. One of the new facilities is a ski jumping area (Figure 19), with two jumps and a landing area with seating for spectators. Adjacent to and part of this landing and viewing area is a ski-out area - which will also serve as the start and finish zone for the Alpine Combination - which constitutes a composite steel-concrete bridge deck with multiple season-dependent purposes. The design of the structure is such, that when the viewing area is subjected to the weight of thousands of spectators, uplift force conditions result at several of the structure's support bearings. At other times, however, load distributions will be very different, resulting in a number of load cases with uplift forces acting for prolonged periods of time.

Spherical bearings with internal uplift protection were selected to address this challenge, with free sliding, guided sliding and fixed varieties required. The design and manufacture of these bearings are illustrated in Figures 20 to 25.

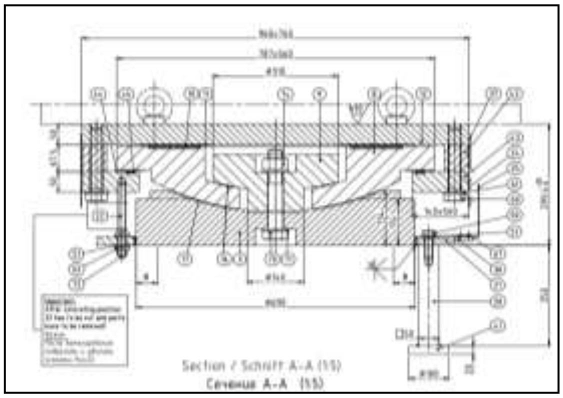

Figure 20. The design of a free sliding uplift bearing (allowing both longitudinal and limited transverse movements).

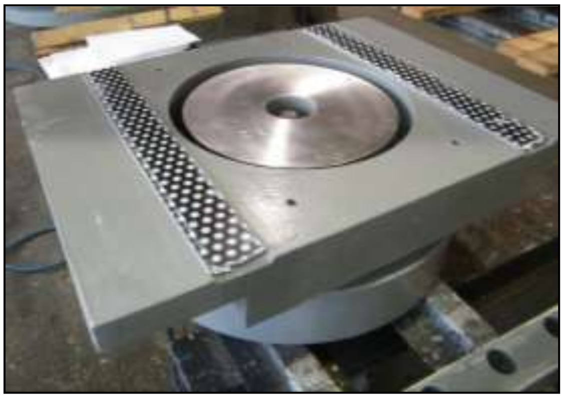

Figure 21. A free sliding uplift bearing during assembly, before placing of the sliding plate on top.

Figure 22. A guided sliding uplift bearing (allowing longitudinal movements, resisting transverse forces), during assembly (before placing of sliding plate on top or guide bars at each side).

Figure 23. The guided sliding uplift bearing shown in Figure 22, following placing of the sliding plate on top but before fixing of the guide bar at one side.

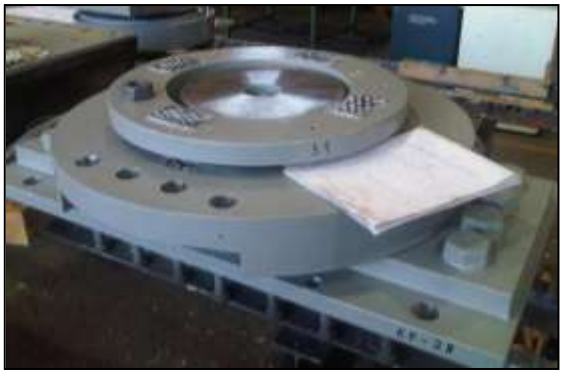

Figure 24. A fixed uplift bearing during assembly (before placing of top plate).

Figure 25. The main uplift-resisting element of the fixed uplift bearing shown in Figure 24.

5 EXCEPTIONAL UPLIFT BEARINGS FOR SPECIAL REQUIREMENTS

Occasionally, uplift bearings, which are already quite special in their own right, must also satisfy very special additional demands. In such cases, the bearing's primary function of resisting uplift as well as downward forces is likely to play a key role in developing a solution, perhaps presenting the greatest challenge to be overcome. This is illustrated by the following example.

5.1 *The special uplift bearings of the Golden Ears Bridge, Vancouver*

The Golden Ears Bridge (Figure 26), near Vancouver, British Columbia, was opened to traffic in 2009 and features an unconventional hybrid cable-stayed design which allows the bridge deck, rather unusually, to rise and fall under the influence of traffic alone. The bridge has three main spans of 794 feet (242m) each and end spans of 397 feet (121m), and the movements of the entire 3175 foot (968-meter) length are accommodated by expansion joints and bearings at the two ends only. The design of the bridge resulted in the following very demanding combination of requirements for each bearing (Spuler et al. 2010):

- Longitudinal movement of 122 inches (3,100mm)
- transverse movement of 2 inches (50mm)
- rotation of 0.039 radians
- downward bearing capacity of 1,034 kipf (4,600 kN)
- uplift capacity of 881 kipf (3,920 kN)
- and all of this with frequent changes between downward and uplift force conditions, many times a day.

A solution based on the spherical bearing type shown in Figure 16 could have been developed to satisfy all force and movement requirements, but the final requirement, for the bearing to be designed to withstand frequent changes between downward and upward force conditions, was defining in this challenge. Since vertical movements, however minute, of one part relative to another could not be ruled out (due to fabrication tolerances and material deformations in particular), it was concluded that the materials used at the sliding interfaces could with time have suffered from the hammering which would result each time the vertical force on the bearing changed from upward to downward. To prevent such hammering, it became clear that the bearing design had to ensure that the sliding interfaces were in a constant state of compression.

A standard bearing type fulfilling these requirements was not known to the bearing supplier, so a special design had to be developed. The final design features a long part which is bolted to the bridge deck and a shorter part which is anchored to the concrete pier below. These parts interact by virtue of their overlapping horizontal plates, which are separated by large, sliding elastomeric bearings (see Figures 27 and 28). Each bearing was constructed with a designed pre-compression force of 337 kips (1,500 kN), which would ensure that no gaping joint occurs at any of the bearing's sliding surfaces under Serviceability Limit State conditions.

Figure 26. The Golden Ears Bridge, during construction

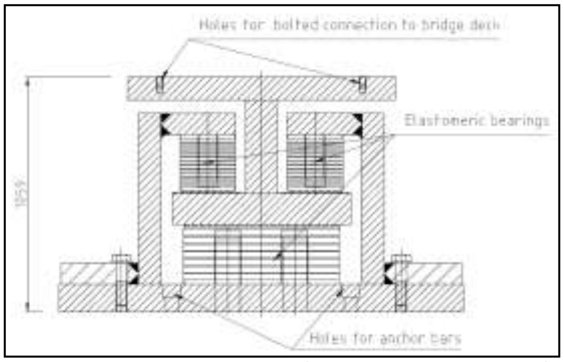

Figure 27. Cross section of pre-compressed uplift bearing. The elastomeric pads have PTFE surfaces (bottom of upper pads, top of lower pad) to allow sliding of the upper part across the lower part.

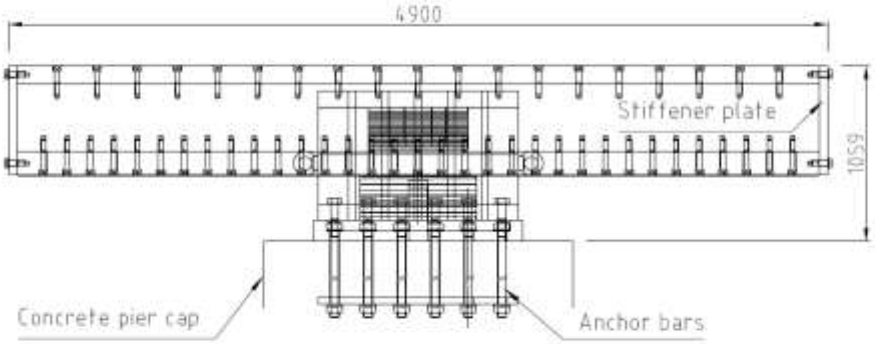

Figure 28. Longitudinal section of bearing - facilitating sliding movements of +/- 5 ft (+/- 1550mm).

Production of bearings of such dimensions presented many challenges not normally encountered in the manufacture of bridge bearings, requiring special measures to be utilized. For example, to ensure the parallelism of critical bearing elements, which could have been compromised by welding distortions, it was decided to bolt, rather than weld, the critical plates together. And the compressibility of each elastomeric bearing was tested after manufacture to confirm theoretical predictions about its performance. Such measures enabled confidence to be gained that these special bearings would perform as required in service.

Figure 29. One bearing being securing on a truck for transport to site.

Figure 30. A bearing during installation on the Golden Ears Bridge.

The fully fabricated bearings (Figures 29 and 30), each weighing 37,000 lb (17,000 kg), attest to the fact that suitably qualified and experienced engineers can develop a solution to almost any uplift bearing supply challenge.

6 CONCLUSIONS

The requirement to facilitate uplift conditions can increase the challenge to design and manufacture structural bearings considerably. Although relatively simple external uplift clamps may suffice in many cases, when load reversals are infrequent, the structural performance of some types of uplift bearing can be significantly enhanced by locating the uplift prevention feature at the bearing’s centre, largely avoiding force eccentricities that can result in unwanted moment forces and prying action. But even this advanced solution may not suffice in some instances, e.g. when a bearing is subjected to frequent load reversals which could result in hammering at sliding interfaces which are not pre-compressed. It is thus clear that the nature and frequency of the uplift condition must be assessed and understood to enable a suitable bearing solution to be proposed and implemented.

REFERENCES

Spuler, T., Moor, G. & O’Suilleabhain, C. 2010. Supporting innovative bridge design - The bearings and expansion joints of the Golden Ears Bridge. *Proc. 3rd FIB Int. Congress*, Washington D.C.