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# BEHAVIOUR AND MODELLING OF LEAD-RUBBER BEARINGS SUBJECTED TO TENSILE ACTIONS

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## Abstract

The general backbone curves for Lead Rubber Bearings (LRB) uses the tension stiffness as equal to the compression stiffness (up to 2G force). This leads to impractical unit loads for the manufacturers bidding for the supply to satisfy very high “ghost” tension forces (generally in MN), together with misleading design loads for the design of the structures and its connections to the isolation plane. Current backbone curves were determined using small units (eg. 180-400mm Dia), stiff rubber (eg G100) and often comparatively large lead cores (eg 60mm). These sizes are much smaller that units that we place under buildings: (600-1400mm dia), with softer rubber (G40-G60), and significantly smaller plug/bearing size ratio.

By including a tension test as part of our production protocol, we have collected a broad data set, allowing us to better determining tension stiffness of LRB units. The tension testing has been undertaken on full-scale LRB of various sizes, heights and lead core diameters. An obvious trend in these data highlights that the units are significantly softer in tension that the current backbone curves utilized in modelling by consultants.

Presented results show that LRB tension stiffness is non-linear in nature, however can be closely approximated to a bi-linear behavior with a defined lead yielding ($Q_{dt}$), and a post yield rubber stiffness ($K_{vt}$). The initial stiffness, attributed to the lead core ($Q_{dt}$), can be approximated from the core diameter, and the post yield tension stiffness of the rubber ($K_{vt}$) can be related back to the compression stiffness ($K_{vc}$) of the unit. There is also a noted scale effect that occurs with smaller diameter stiffer units converging on $K_{vc}$ approx. equal to $K_{vt}$, which highlights issues with small scale testing and extrapolation to real size units.

Results in the data collected show the effective axial tension stiffness ($K_{vt,eff}$) of LRBs varies according to the size of the unit and has a ratio of $K_{vt,eff}/K_{vc}$ from 1/10 (small diameter) to 1/80 (large diameter) .

The axial tension testing also revealed the LRBs can sustain significant elongation while remaining below the currently accepted cavitation limits (between 2G - 3G). Testing for the unit results elongation will be in the order of 20-30mm before the lower bound cavitation forces are reached (10-12% tension strains in unit rubber height), however the tensile stiffness from the test results is much softer than the recommended backbone curves of $K_{vc}$ up to 2G loads.

From the data presented in this paper from approximately 190 full scale tests, there is minimal degradation in the post yield rubber stiffness upon repeat cycles, when working below 3G forces. The maximum MCE uplift displacements from the computer model should be set as the lower bound limits for the elongation of the units tested.

This paper provides a simplified method of modelling tension stiffness in LRB units to more accurately predict analysis tension forces in units. Actual tension stiffness should be verified by prototype, and production testing

*Keywords: Lead-Rubber Bearings, Tension stiffness, Non-linear modelling*

# 1. Introduction

The adoption of base isolation as design solution for mitigation of earthquake damage potential and increased performance is becoming more popular even for very tall buildings and irregular buildings' shapes. In these situations though the isolators are more prone to developing tensile actions and consequently characterization of the tensile response of the units becomes critical in design. By overestimating the tensile stiffness the design loading on the bearings and the supporting structure would appear as unrealistically large and unsustainable.

For the representation of the tensile response of rubber isolators, Iwabe et al [2] amongst others, through testing on rubber and lead rubber bearings, proposed an equivalent bilinear model for characterizing the tensile stress-strain response, where the initial stiffness $K_{t1}$ is obtained by connecting the loading start point with the tensile load corresponded to the shear modulus G. The elastic limit load $P_t$ is obtained from the intersection point with the hysteresis loop in shifting the initial gradient to the deformation corresponded to the tensile strain of 1%. However the authors did not observe rupture even if 100% in tensile strain was given with offset shear strain of 200%. The authors observed tensile linear response up to 5-10% strain, with significant drop in tensile stiffness at about 25% elongation. The initial tensile stiffness has been assessed in the order of 1/10 of the corresponding value in compression.

An alternative non-linear model (Origin tensile stiffness strain model) has been proposed by Yang et al. [7], with similar results in terms of tension/compression stiffness ratio.

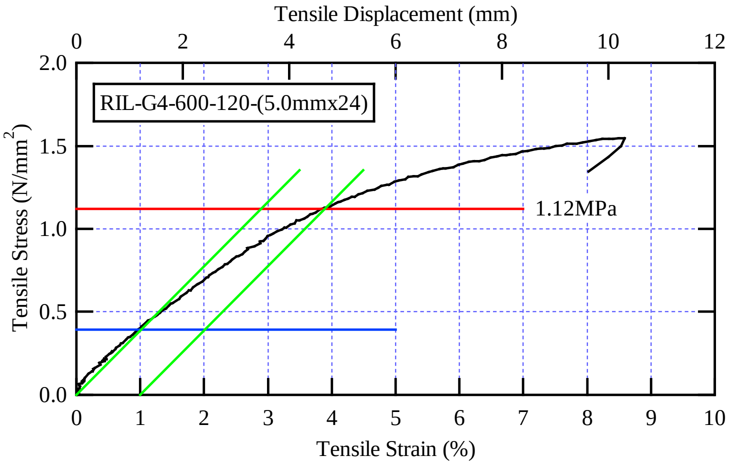

Fig. 1 – Bi-linear tensile stress-strain model, as proposed by Iwabe et al [2]

Takayama et al. [1], through testing on 500mm Rubber Bearings (without lead core – G=0.55MPa), found that bearings can sustain axial deformations with no failure up to 1MPa tension, with failure occurring at very high strain levels (48% strain under 300% shear strain). The authors also observed that laminated rubber bearing has large capability for tensile deformation, with the tendency for the tensile behavior to develop a non-linear type of response only at very high strain levels (25% elongation). Failure has been observed only under the shear strain of 300% and breaking tensile strain was 48%.

Other research documents [3, 4] show as theoretical limit at onset of cavitation has been in some way set without a robust validation, with several tests showing that bearings may undergo larger tensile strains without damage.

Previous studies performed in the US tend to suggest more strict limits, with the assumptions that multi-chain damage, damage of the micro-structure, and micro-void formation in cross-link polymers will likely develop under tensile elongation [4]. Therefore the suggestion/recommendation that uplift, or tension, in elastomeric bearings is undesirable and efforts should be made in the design process to avoid uplift on the isolation system.

We should also note as most of the existing data currently available from previous tests [4, 5] refer to small scale units (500mm dia or lower). These tests provide tensile stiffness estimates similar to the correspondent value in compression. An example is the work of Oh et al. [4], resulting in the response curve shown in Fig. 2a. The study also revealed as the units undergo tensile loading up to 300% strain without rupture.

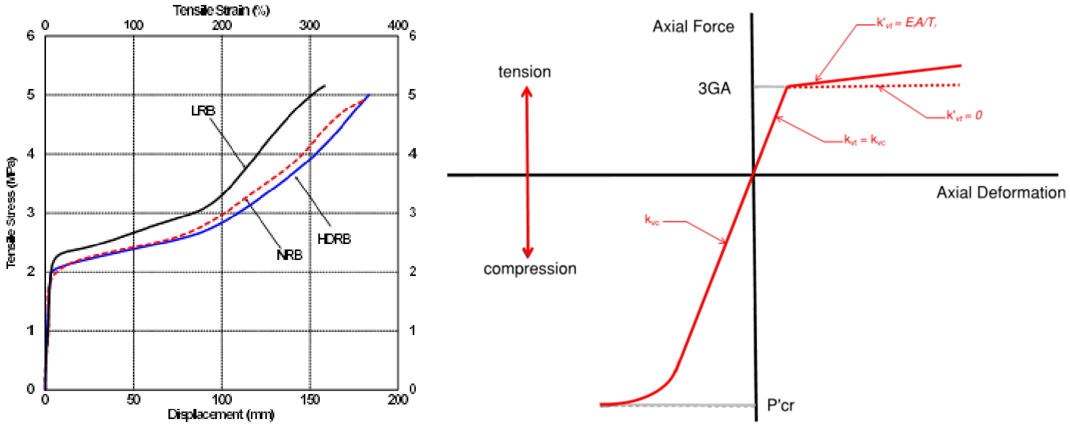

Fig. 2 – Bi-linear tensile stress-strain model, as proposed by Oh et al [4] (a), – Bi-linear tensile stress-strain model, as proposed by Kumar et al. [6] (b)

Further, Whittaker et al. [5], based on [6], set the cavitation limit to 3G, and the elastic tensile stiffness equal to the compression stiffness, as shown in Fig. 2b.

From all of the above it appears as there is no clear indication on how to approach modelling/evaluation of the response of rubber bearings when subjected to tensile actions, and this is reflected in the current international design codes (not allowing for tension to develop, or limiting this value to a pre-set level – 1-2G). The study presented in this paper aims to provide some clarification on the tensile response of Lead Rubber Bearings by presenting the outcomes from the most extensive tensile campaign ever, with almost 190 units tested. The paper focuses on the evaluation of the initial stiffness of the bearings in tension, while the calibration of an equivalent non-linear model, as well as the response of Rubber Bearings, will be subjects for future studies.

## 2. Testing procedure

The Robinsons Seismic test facility is Kuala Lumpur has a double acting shear rig for testing large LRB units. Several years ago this rig was modified to enable tension tests to be completed.

The data collected is based upon a pure axial tension test, where tension is applied over both units – however transducers are applied and record only the elongation in one of the units.

Fig. 3– Tension testing on 1020LRB190 Unit

The tension stiffness can then be recorded, and compared to the compression stiffness of the same unit (also part of our production protocol).

Tests have been performed on six different units, as summarized in Table 1, where the force at 1G tensile strain is also shown as reference for the response evaluation. A schematic representation together with the geometric data of one of the units tested is shown in Fig. 3.
Tensile loading tests have been performed on full scale units featuring various external diameter and lead core size. The rubber compound has a shear modulus of 0.45-0.55MPa and monotonic tests have been performed up to about 20mm tensile elongation without any deterioration of the bearings. The peak tensile force during testing has been limited below the 2G tensile stress limit, at which damage associated with cavitation of the rubber compound may occur.

Table 1 – Properties of the LRB units tested

| **Unit** | **Bearing Diam.** | **Plug Diam.** | **Rubber Area ($A_r$)** | **G** | **Rubber height** | **1G x $A_r$** | **# Units** |
|---|---|---|---|---|---|---|---|
| - | mm | mm | $mm^2$ | MPa | mm | kN | - |
| 770LRB120 | 770 | 120 | 454353 | 0.45 | 220 | 204 | 44 |
| 820LRB100 | 820 | 100 | 520248 | 0.55 | 280 | 286 | 44 |
| 870LRB155 | 870 | 155 | 575599 | 0.55 | 220 | 317 | 19 |
| 970LRB155 | 970 | 155 | 720112 | 0.55 | 280 | 396 | 48 |
| 1020LRB190 | 1020 | 190 | 788775 | 0.55 | 280 | 434 | 25 |
| 1120LRB190 | 1120 | 190 | 956851 | 0.55 | 280 | 526 | 7 |

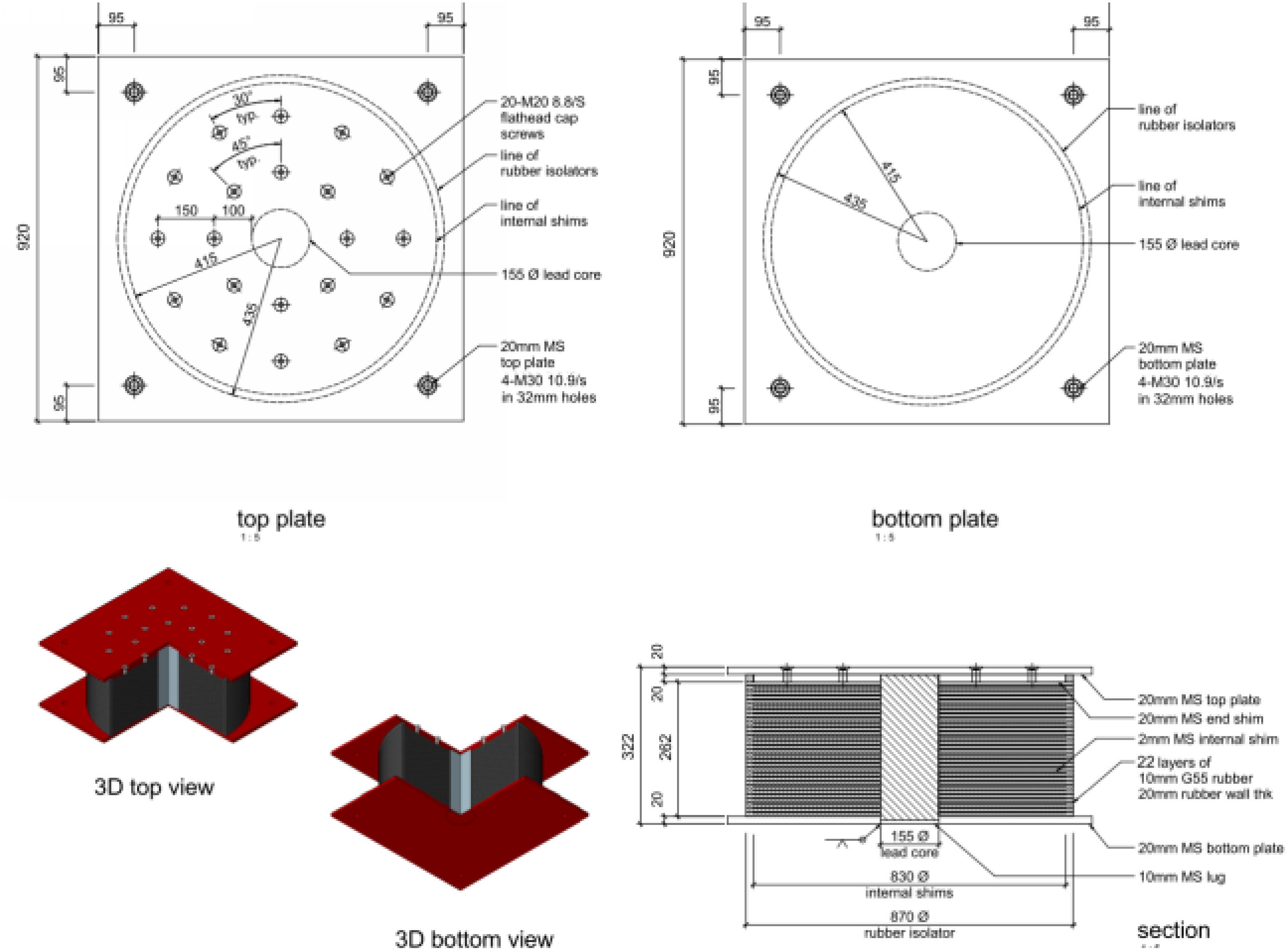

Fig. 3 – Schematic representation and geometric data of one LRB unit (870LRB155)

## 3. Test results

The tensile response of the bearings revealed the tendency to develop a non-linear response at low strain levels, characterized by an initial “yielding” threshold $Q_{vt}$ well below any cavitation may occur. This may be partially explained by the presence of the lead plug and the restraining effect that this would have when confined. Further research is required to clarify this lead-extrusion-type mechanism of the core between confining steel shims, however what is clear is the non-linear nature of the response. For this reason, the initial stiffness of the bearings in tension should be defined as the secant value at the design axial elongation, as graphically shown in Fig. 4, with reference to the range of axial displacements covered in this study (1 to 5mm, 0.4% to 2% elongation). Thought this comparison may be interesting under a scientific point of view, for practical applications the design elongation demand would likely be only marginally affected by any stiffness used within this range.

Fig. 4 to Fig. 9 provide sample force-displacement curves amongst the 187 tests performed, including tests at large strains. It is apparent from these curves as no damage occurred even at large levels of axial elongation.

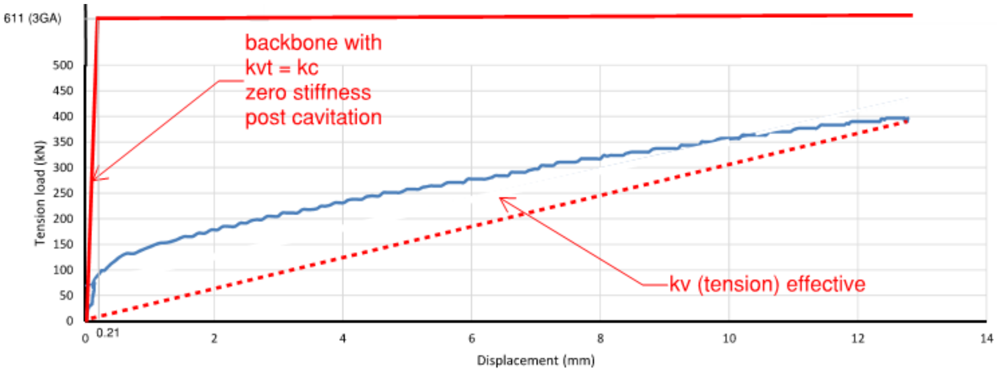

Fig. 4 – Sample tensile force-displacement response (770LRB120)

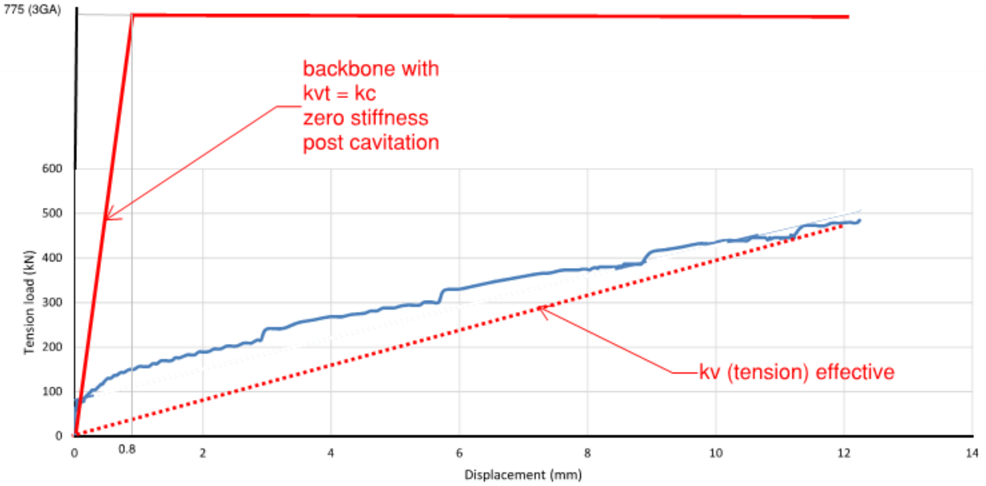

Fig. 5 – Sample tensile force-displacement response (820LRB100)

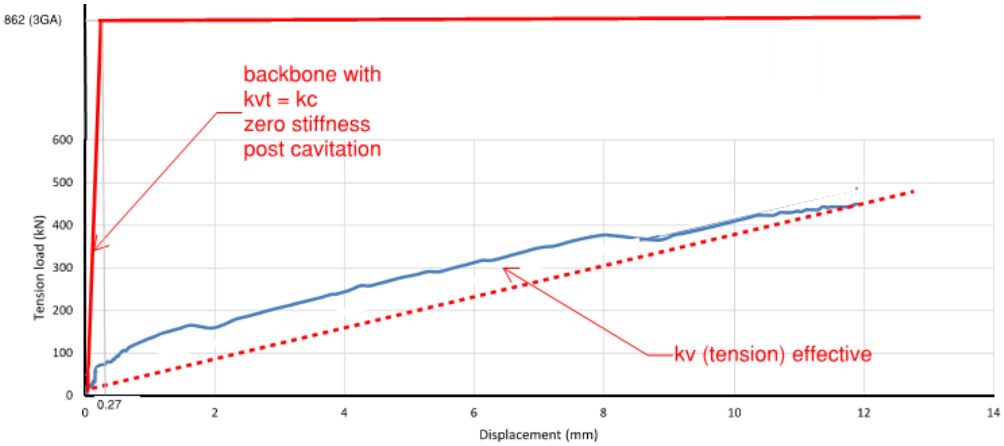

Fig. 6 – Sample tensile force-displacement response (870LRB155)

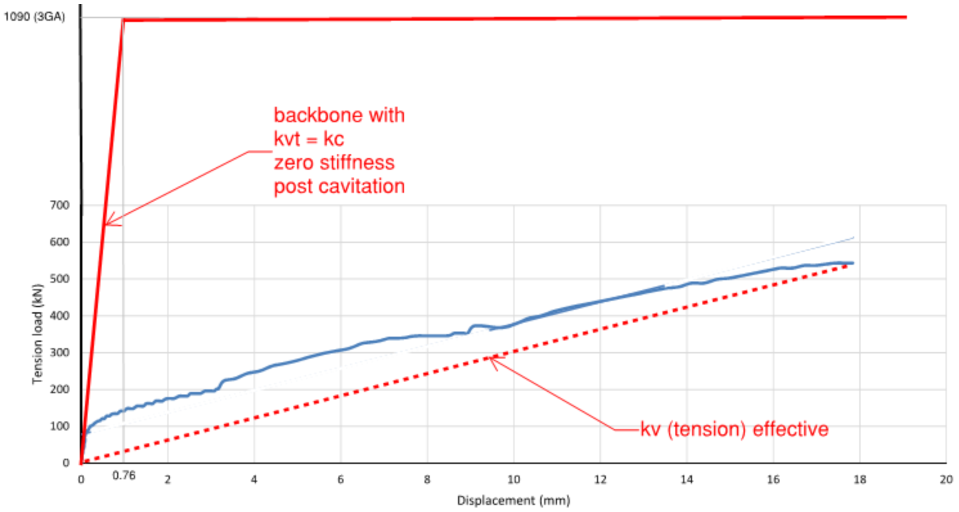

Fig. 7 – Sample tensile force-displacement response (970LRB155)

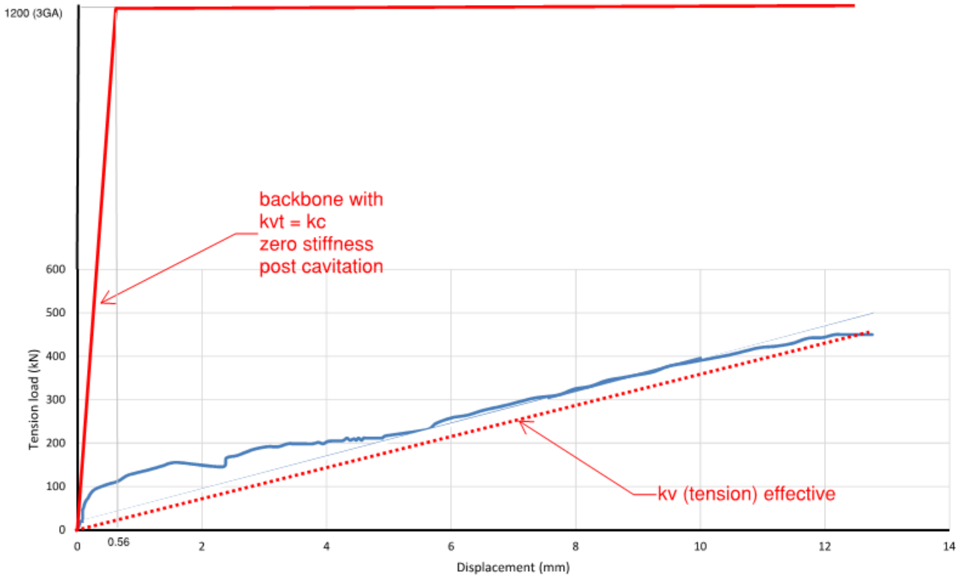

Fig. 8 – Sample tensile force-displacement response (1020LRB190)

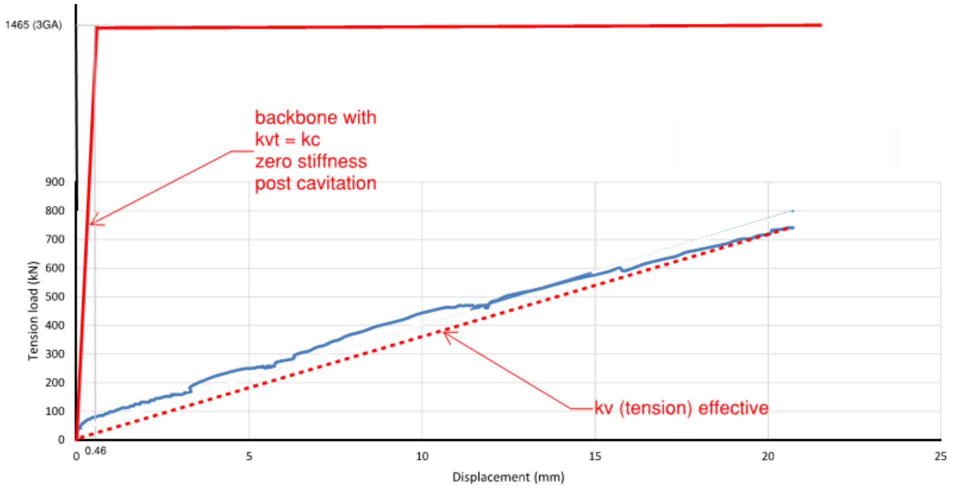

Fig. 9 – Sample tensile force-displacement response (1120LRB190)

The results presented in Fig. 10 show the ratio between the compression and tension stiffness for the specimens tested at the reference elongation of 5mm (2% strain). Results are presented with reference to the effective (secant) stiffness of the units in tension ($K_{vt,eff}$) in consideration of the tendency observed for LRBs to develop a non-linear response.

These results show as the distribution of the test data is fairly constant, with the majority of data included within the +/- standard deviation range from the median value. For all the units tested, the ratio between the compression and tension stiffness is within 20 and 80 at 2% strain.

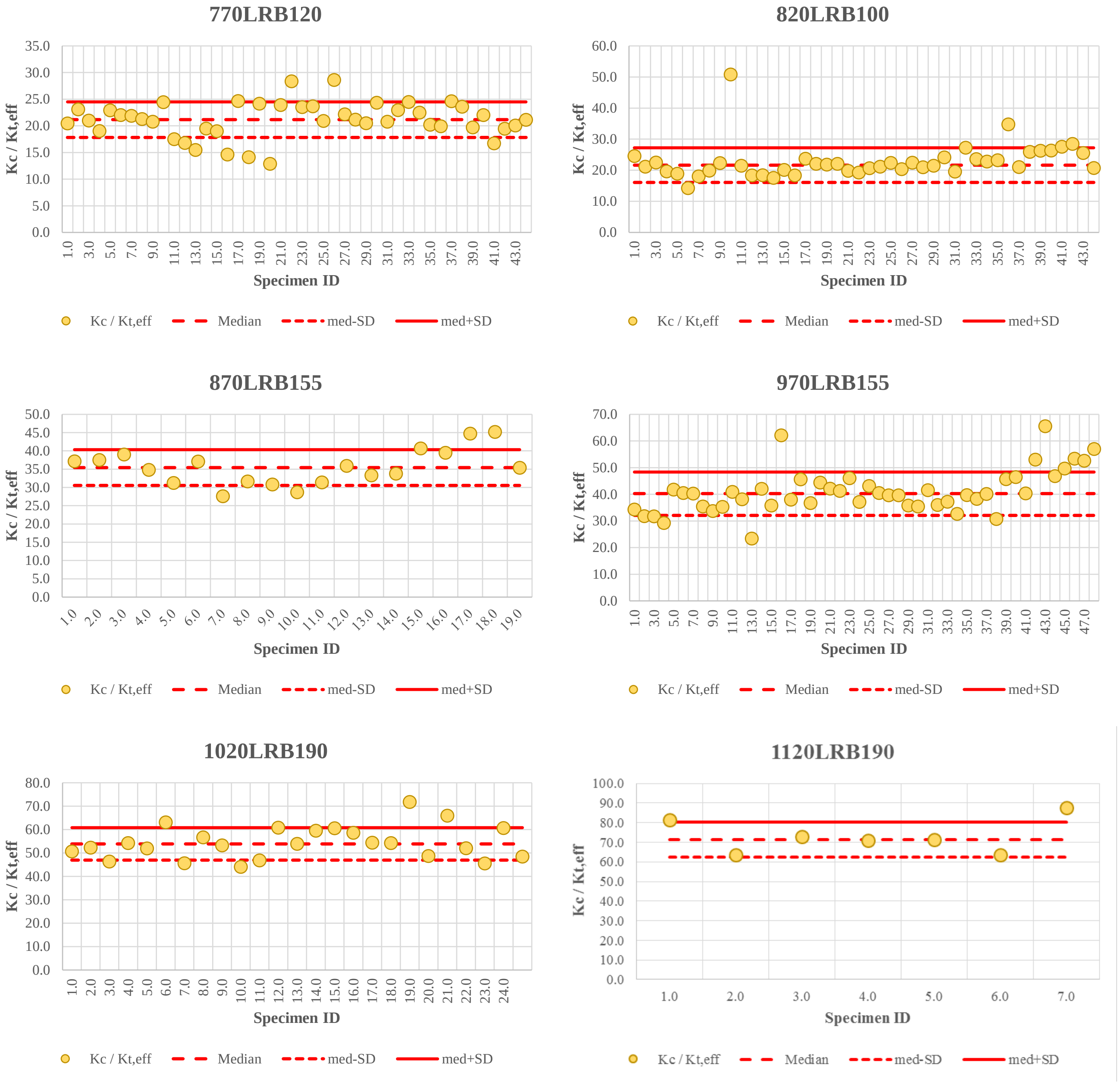

Fig. 10 – Compression/Tension stiffness ratio for the different units tested

The Compression/Tension stiffness ratio has been evaluated against the bearing diameter and the lead plug diameter in Fig. 11 to Fig. 15 for different levels of axial strains within the practical range of the units in many applications. These results show as the tensile stiffness decreases with the bearing size and the plug diameter and, for the range of LRBs covered and the tensile strain range adopted, it varies between 10 and 80. The tendency is for this ratio to increase almost linearly with bearing/plug size.

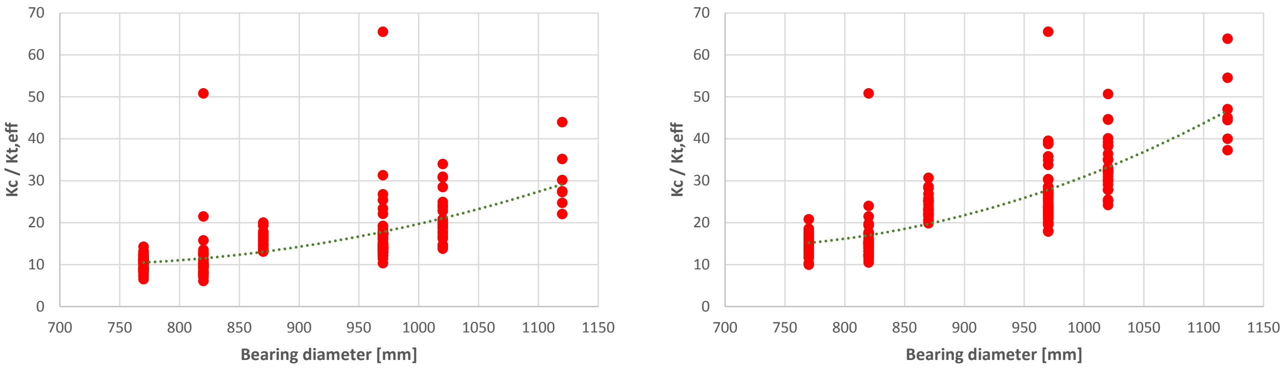

Fig. 11 – Compression/Tension stiffness ratio vs LRB diam: $K_{vt,eff}$ @ 1mm elongation (0.4% tensile strain) (a), $K_{vt,eff}$ @ 2mm elongation (0.8% tensile strain) (b)

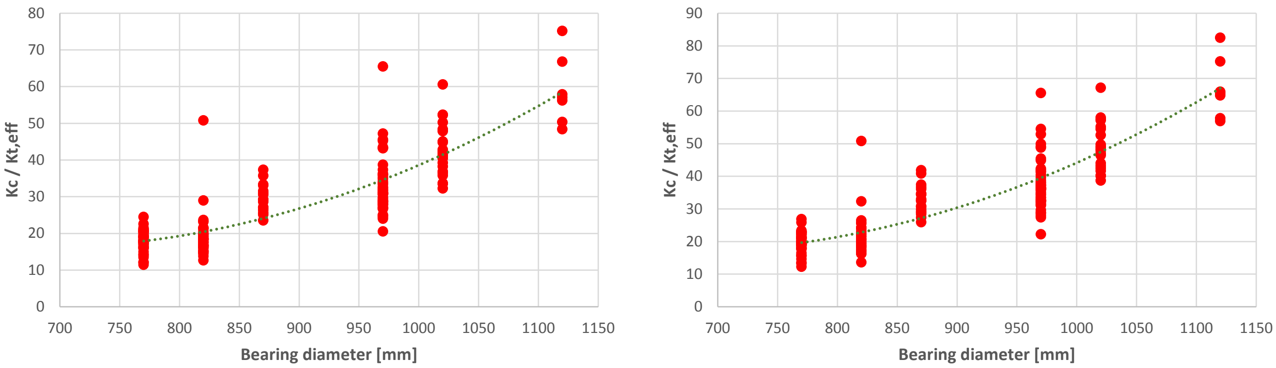

Fig. 12 – Compression/Tension stiffness ratio vs LRB diam: $K_{vt,eff}$ @ 3mm elongation (1.2 % tensile strain) (a), $K_{vt,eff}$ @ 4mm elongation (1.6% tensile strain) (b)

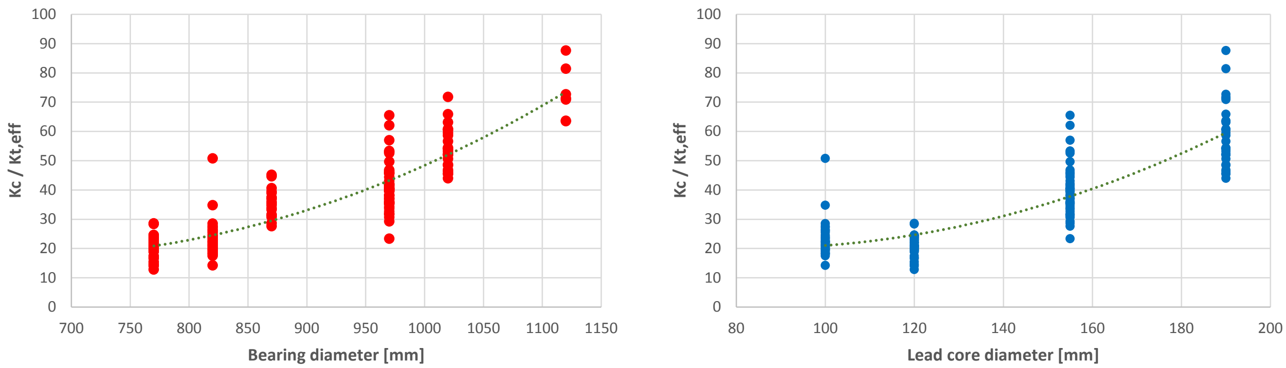

Fig. 13 – Compression/Tension stiffness ratio: $K_{vt,eff}$ @ 5mm elongation (2% tensile strain): $K_{vc}/K_{vt,eff}$ vs LRB diam (a), $K_{vc}/K_{vt,eff}$ vs Plug diam (b)

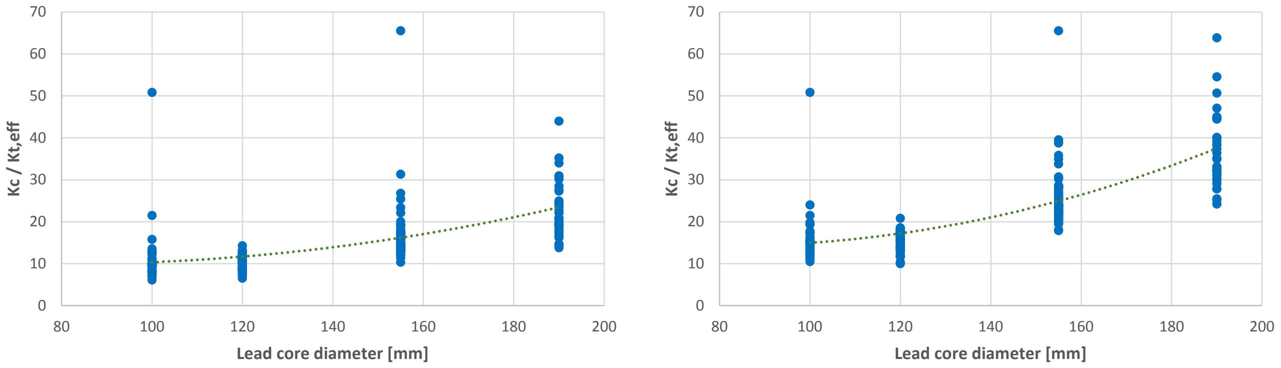

Fig. 14 – Compression/Tension stiffness ratio vs Plug diam: $K_{vt,eff}$ @ 1mm elongation (0.4% tensile strain) (a), $K_{vt,eff}$ @ 2mm elongation (0.8% tensile strain) (b)

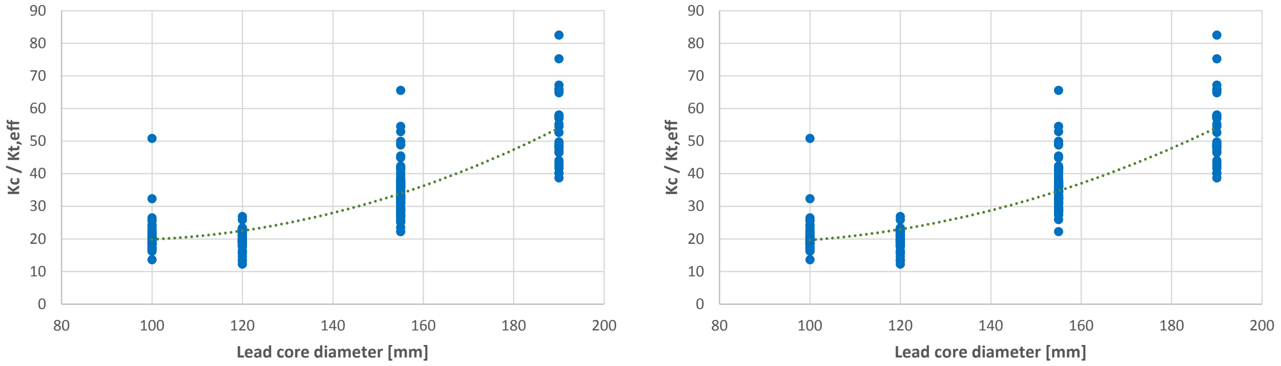

Fig. 15 – Compression/Tension stiffness ratio vs Plug diam: $K_{vt,eff}$ @ 3mm elongation (1.2 % tensile strain) (a), $K_{vt,eff}$ @ 4mm elongation (1.6% tensile strain) (b)

## 4. Conclusions

The study summarized in this paper represents an extensive testing campaign to critique the tensile behavior of LRBs. Results show as the ratio between the elastic stiffness in compression and tension depends on the size of the units and the lead core. Results are presented for a wide range of deformations to cover the likely possible design scenarios and provide the designers useful references for assessing the axial properties of the units when prone to tensile actions. The authors suggest a few iterations to identify the tensile stiffness coefficient consistent with the actual loading scenario. Thought this comparison may be interesting under a scientific point of view, for practical applications the design elongation demand would likely be only marginally affected by any stiffness changes used within this range. Comparison between analyses where lower stiffness values are used produce only a minor increase in the actual calculated uplift displacement, however the forces derived from modelling are significantly corrected.

Thought the extensive set of data reported in this paper offers the basis for a simplified methodology to be used when dealing with modelling tension stiffness in LRBs to more accurately predict analysis tension forces, the authors believe that the actual tension stiffness should be verified by prototype and production testing. Validation through testing is key to make sure that the actual performance is consistent with the design assumptions, avoiding larger-than-design loading on the structure and foundation, as well as to ensure a reliable behavior of the units subjected to tensile actions.

Calibration of an equivalent non-linear model, as well as the response of Rubber Bearings, will be subjects of future studies, which include axial tension of units without lead cores, tension/shear combined loading, larger elongation demands on the units to find the upper bound limits

## 5. Acknowledgements

Dario your dedication to the analytical review and summary of our data is excellent, and I appreciate your patience with my busy schedule in getting time to review and complete this. grazie amico mio

## 6. Copyrights

## 7. References

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