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BIAXIAL TESTING FACILITIES FOR ANTI-SEISMIC DEVICES

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Abstract: *Onerous load-deformation tests are required by earthquake engineers and the relevant Standards (eg EN15129, ISO22762). Several bespoke test machines have been designed and built, throughout the world, to meet this need, but they all differ, not only in specification but also in basic design. After a brief review of what is available, the paper will describe a new versatile machine that has been designed and built by TARRC for testing full-sized isolators in combined compression and shear. It can also be configured to do other types of test, including uniaxial tests required for energy dissipating devices.*

Although the Standards call for tests at, or near, full-size, it is invaluable to also test at small scale, including test pieces for material properties. The relative merits of choice of scale for the various properties will be discussed. In this context a TARRC facility for investigating coupling effects for rubbery materials in general biaxial shear, including the possibility also of maintaining a given compression (ie third axis) load or deflection will also be presented. This proved invaluable in a recent assessment of the biaxial shear behaviour of a high damping natural rubber material (Ragni et al, 2018).

Introduction

Design calculations of engineering properties of rubber components

TARRC started life as the British Rubber Producers' Research Association (BRPRA) in 1938, aimed at supporting the exploitation of Natural Rubber (NR) by industry by elucidating a scientific and technological framework for rubber properties. Within a few years BRPRA included a team working on Engineering Applications, now known as the Engineering and Design Unit of TARRC. Our mission is to identify engineering applications for rubber, and develop design methodology to support them. Because of its excellent mechanical strength, NR remains the dominant choice for meeting arduous mechanical loading conditions, especially if the component is bulky and not exposed to temperature above the ambient range, though the mathematical design principles (eg Gough & Lindley, 2018) could be readily applied to design of components using synthetic rubbers.

This paper is focused on one success story of TARRC's development and research of rubber engineering applications: laminated rubber-steel structural bearings. These have successively been exploited as bearings to accommodate thermal expansion of bridge decks, anti-vibration mounts to isolate buildings from ground-borne vibration, and earthquake isolation bearings. In each case, the detailed design needs to be adapted, based on the material properties, using design equations based on the shear stress-strain properties of the material.

Because the shear modulus *G* of rubber is about three orders of magnitude less than its bulk modulus, the local state of strain of rubber in most engineering components approximates to simple shear. For rubber-steel laminates, the shear strain is approximately uniform if the rigid inserts move parallel to each other, and stiffness is not affected by "shape factor", whereas the shear strain is non uniform and the stiffness is affected by shape factor if the rigid inserts undergo relative movement orthogonal to their plane, changing the thickness of the rubber layer.

It follows that determination of the stress-strain behaviour in simple shear is the key material test for such engineering components. From this behaviour, the load-deformation of laminated structural bearings may be calculated with good accuracy from simple analytical expressions, obviating the need for numerical analysis for routine design work.

Standards call for time-history analysis for checking response of important structures to earthquake excitation. Material stress-strain data is invaluable for such checks in earlier stages

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of a project, even though Standards may require validation from tests done at or near full-scale on the actual isolators to be used. TARRC was a key contributor to the introduction of the British Standard for measuring dynamic properties of rubber in simple shear using a double shear test piece (Hall & Thomas, 1973; BS903 A24:1976).

Full scale tests of seismic isolation bearings

Onerous load-deformation tests of seismic isolation bearings are required by earthquake engineers and the relevant Standards (eg EN15129, ISO22762). Such tests are very challenging, not least in the perceived need to meet actual high rates, deflections, loads and moments, but also in tight tolerances on potential imperfections with the tests, such as parasitic friction, parallelism of the bearing faces, and variation of compression load during shear. Several bespoke test machines have been designed and built, throughout the world, to meet these difficulties, but they all differ, not only in specification but also in basic design and in quality of the results and compliance with the specifications. These challenges and variety of solutions will be briefly reviewed and illustrated with alternative design concepts, before presenting the design of a new machine recently commissioned at TARRC.

2. Characterisation of simple shear stress-strain behaviour of rubber

Uniaxial tests

Both double shear and quadruple shear (Figure 1) have been the subject of Standards. They differ in the boundary condition for the normal direction – constant length for double shear and zero force for quadruple shear. At small shear strains this difference will be negligible, but as a normal stress proportional to the square of the shear strain is required to maintain simple shear (Treloar, 1978) for a neo-Hookean material (the simplest elastic model in finite elasticity theory), it can be appreciated that the departures from simple shear will be increasingly divergent for the two test pieces. Standards for both geometries do try to limit such imperfections, typically by requiring the length of the rubber layer(s) in the direction of shear is at least 4 times the thickness in the orthogonal direction, but even so, nominal simple shear tests always depart somewhat from the perfection of simple shear (Gregory & Muhr, 1999; Gough, Muhr & Gregory, 2000).

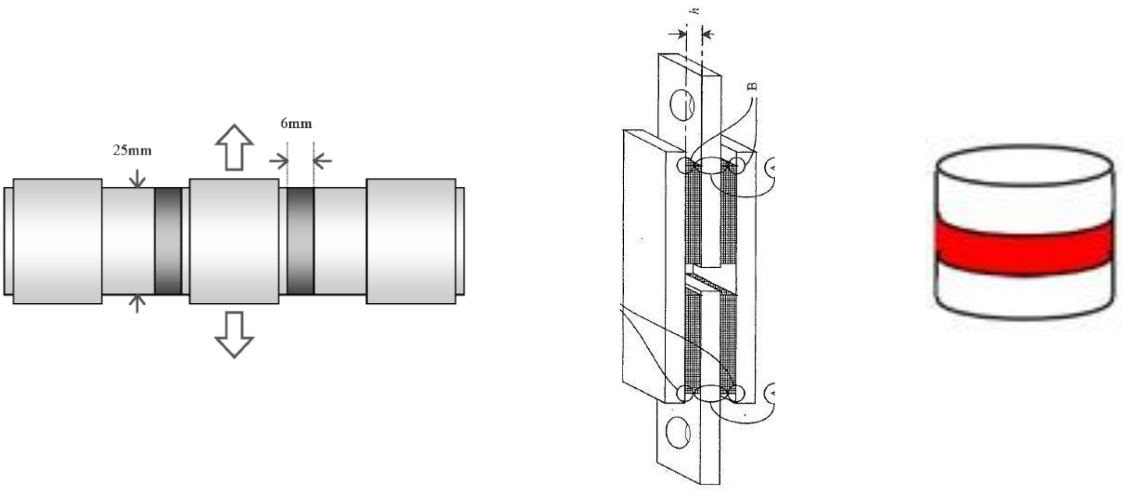

Figure 1 Simple shear test pieces for material tests. Left, cylindrical double shear test piece developed at TARRC; centre, quadruple shear test piece according to ISO1827; right, single layer cylindrical test piece used in the biaxial shear rig at TARRC for tests reported by Tubaldi et al. (2017), Ragni et al. (2018) and Ahmadi et al. (2019).

Biaxial test facility at TARRC

Figure 2 shows a rig designed and built at TARRC for performing biaxial tests on small test pieces, including material characterization test pieces for rubber in biaxial simple shear. Two plates sliding on horizontal orthogonal linear bearings are employed to give the bidirectional horizontal displacements to the specimens without torsion, or rotation out of plane. Each plate is attached to a horizontal actuator, each capable of imposing any independent time-history demand and with maximum load and stroke capacities of 10 kN and 150 mm respectively. A sliding plate on a vertical linear bearing can be used to impose a vertical load, or fixed at a given displacement. The servohydraulic actuators are fitted with load cells, but these measure not only the force required to deform the test piece, but also that to overcome the frictional resistance of the linear bearings that accommodate the orthogonal horizontal displacements at top and bottom of the test piece. For this reason a triaxial load cell is introduced between the test piece and the lower linear bearing, for measuring all three orthogonal forces applied to the test piece, free of the additional frictional and inertial forces needed to impose the motions on the bearing blocks. The servohydraulic actuators may be commanded with any displacement time-history of interest, so that the test piece may be subjected to any trajectory in biaxial simple shear space that is of interest. Huang (2002) has provided a set of simple trajectories for characterizing material behavior, some of which are shown by Ahmadi et al. (2019), and the rig has been used to apply these to a high damping rubber used in isolation bearings to develop a fully biaxial non-linear model inclusive of strain-softening effects (Tubaldi et al., 2017; Ragni et al., 2018).

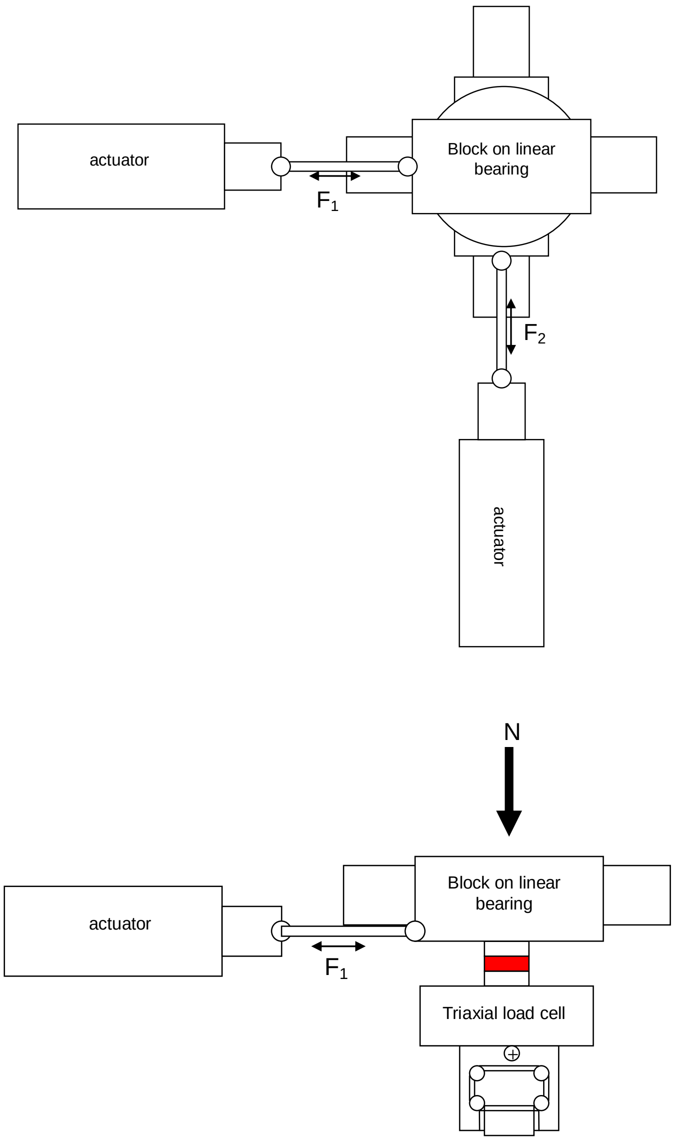

Figure 2. Test rig for performing general biaxial deformations Top, plan view; Bottom, elevation, showing position of test piece.

3. Bearing test machines

The main issues that had to be investigated in the development of seismic isolation bearings were (1) to have a sufficiently high horizontal deflection capacity while bearing full load (2) to check that the horizontal stiffness and energy dissipation under realistic conditions of load/displacement and rate would meet the requirements. Testing played a key role in the initial R&D, undertaken by TARRC in the UK and Delfosse in France, to demonstrate that these were the case, initially using small scale bearings under deadload. At TARRC, concrete slabs were supported by four model bearings, and the lateral force-deflection behaviour measured for successive increments in the load borne using pull-back tests, to check the horizontal stiffness and stability under the combined vertical load and shear deflection. Delfosse carried out similar experiments, supporting a skip on four model bearings, and checking the behavior of the bearings as it was filled with water.

Once it was established that the bearings had satisfactory behavior, TARRC commissioned shaking table tests at the University of California at Berkeley, on scaled superstructures and bearings of approx. 150mm plan dimension. Mulitaxial load cells were introduced under the bearings to monitor the dynamic loads, and the displacements were also monitored with transducers; the tests confirmed the good behavior of the system (Derham et al., 1980).

A thorough testing regime was used for the prototype and production bearings in the case of the San Bernadino County Foothill Law and Justice Centre, completed in 1985 - the first project using high damping natural rubber bearings developed by TARRC. It was the fourth building to be protected from earthquakes using rubber isolators, and each of the three predecessors used different types of bearing. Figure 3 shows the quasistatic Production Test machine for this project, designed and built at EERC, UCB. At that time there was no machine capable of testing the dynamic properties of such large bearings (diameter 760mm, design deflection 380mm, frequency 05Hz), and full reliance was placed on material tests for the latter. About 3 years later, EERC built a dynamic testing rig (Figure 4) for reduced scale isolators, being the same size (150mm in plan dimension) as had been used for the shaking table tests.

Figure 4 shows the design, schematically, of a double shear rig used to test all the lead plug bearings used to isolate the NZ parliament building, (the William Clayton building), opened in 1983. A large double shear rig of this type was built for testing bearings for the Te Papa museum in Wellington, NZ (Robinson, 1995). The ARS laboratory in Frignano (CE) of the Campania Region Competence Center BENECON has a similar design of rig, with 4.5m long reaction struts for the shear force, providing space for the shear actuator (1MN maximum load,1m stroke) and constraining the relative angle of the bearing end faces (Dolce & Serino, 2009).

All of these techniques try to permit the bearings to change in vertical height as they are sheared, as is a necessary consequence of the mechanical response to shear deflection under a constant axial load. This feature introduces some serious challenges for test rig design:

- In a dynamic rig, it is challenging to maintain a perfectly constant axial load while accommodating height drop. This contrasts with the load conditions in the field, for which (leaving aside the fluctuations in vertical load caused by overturning moment of the building) the vertical load is strictly constant, so does no net work. If the control of the vertical load in the test rig is not perfect, there is likely to be net work (whether positive or negative) done by the vertical actuator over one cycle of horizontal displacement. It follows that it would not be reliable to measure the energy dissipation by the bearings based on load-displacement data for the shear actuator alone. As a critical quantity required from the dynamic test is the energy to shear dissipation, test data obtained from the shear actuator alone could be very misleading.
- Mechanically, it is a challenge to prevent the platens from tilting under the influence of the moment that the bearing will exert on them as it is sheared. In the Robinson machine (Figure 5), the beam and pivot mechanism to suppress the tilting will result in a discrepancy between the force applied by the compression actuator, and the actual compression force on the bearings

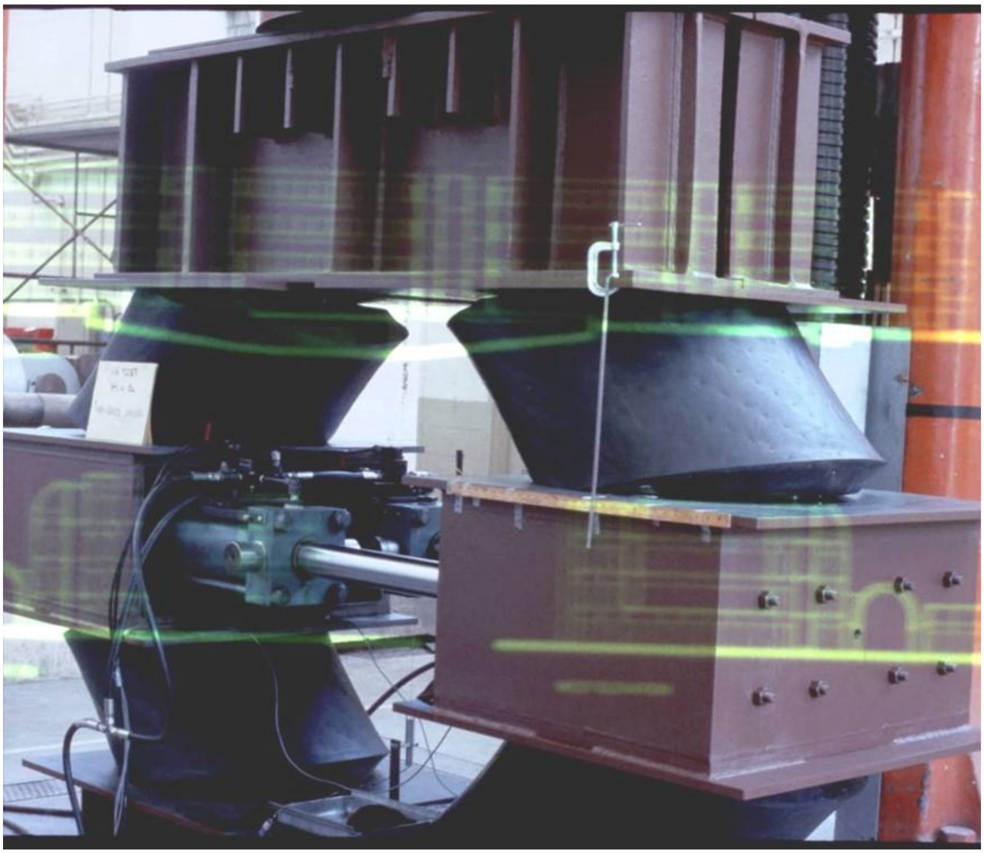

Figure 3. Quasi-static Quadruple full-scale bearing rig for production tests on the FLCJ bearings under design load and design deflection, University of California at Berkeley.

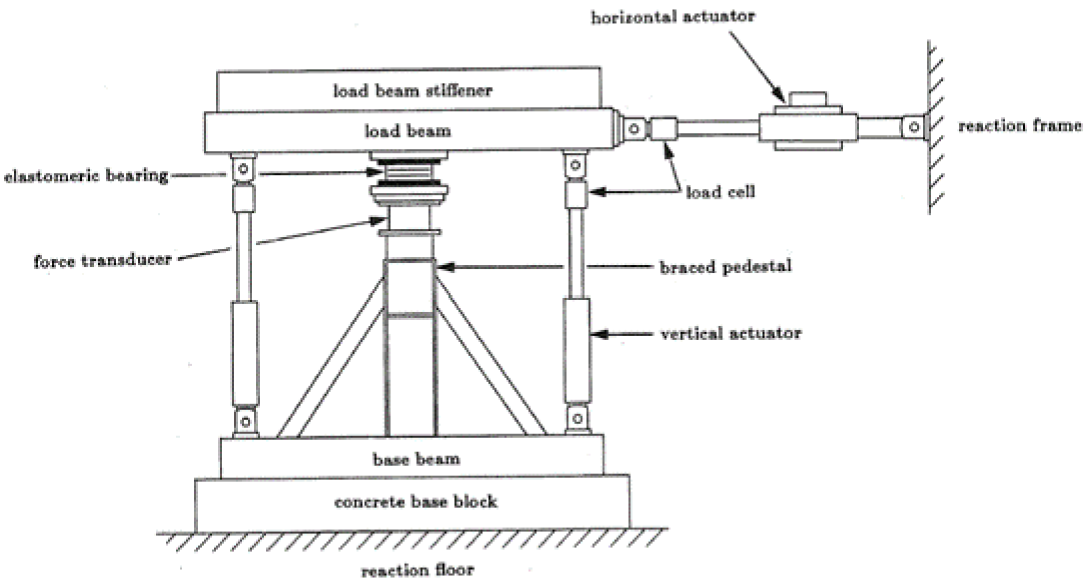

Figure 4. Single bearing test rig for dynamic characterization of scaled bearings, University of California at Berkeley (Kelly, 1991).

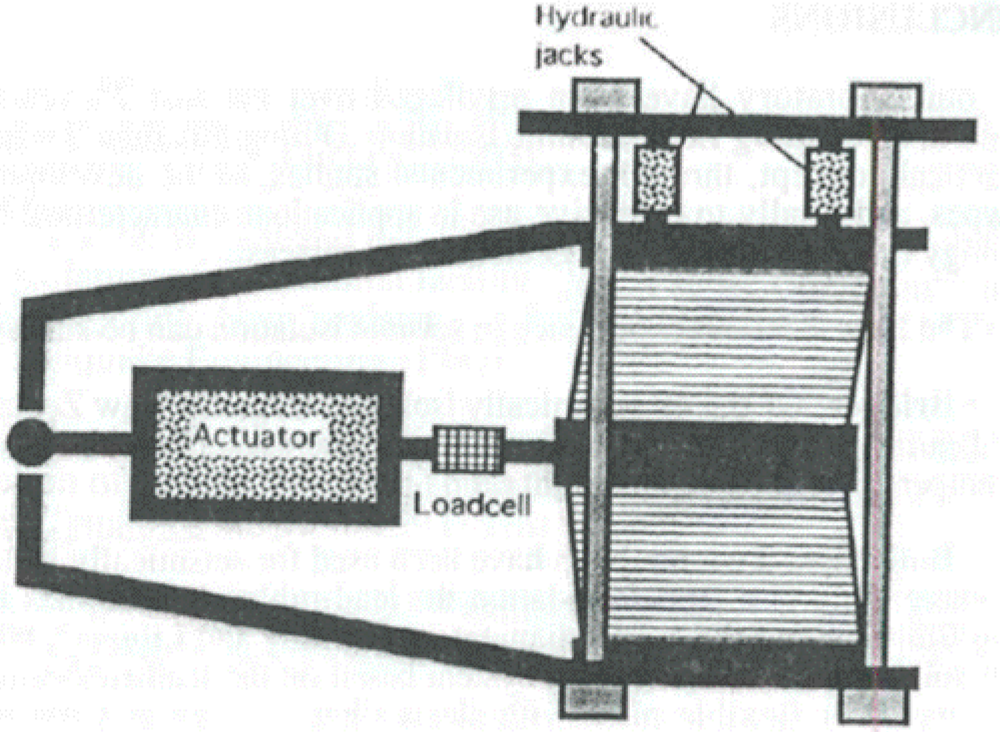

Figure 5 Schematic diagram of double shear testing rigs designed for testing lead-plug isolators developed by the DSIR, New Zealand (Robinson, 1995)

4. New test machine at TARRC

TARRC set itself the ambitious task of not only scaling up the requirements of the older machines reviewed above – ie to enable testing of both the static and the dynamic capabilities of full scale isolators, but also in a sufficiently versatile way that additional tests could be done using the new test machine, such as measurements of the rotational stiffness of bearings, which is a significant challenge in itself (Gough et al., 2006). The tests we would like it to be capable of are outlined in Tables 1 and 2, as these it would hope would create a demand from customers who could help the machine to earn its keep. However, TARRC also wanted the machine to be sufficiently versatile to be used as a research tool for developing bearings or other large rubber components for new purposes.

Initially, for seismic isolators, the layout was envisaged to be double shear, similar to the Robinson machine depicted in Figure 5. However, it was pointed out that Clause 8.2.4.1.5.2 of EN15129:2009 states that “The equipment should preferably allow only one isolator to be tested at a time” even though “the double shear configuration may be used”. The working design of the machine was then adapted to enable the single shear configuration. This was a major complication, entailing not only a challenge to supply a sufficient moment reaction to the platens at the bearing ends, to suppress relative rotation (this needs to be less than 0.003rad, according to Annex G of EN15129:2009), but also the incorporation of a sliding bearing system to accommodate the shear displacement, and a means of measuring shear load on the bearing itself, ie not contaminated by the parasitic friction due to the sliding bearing.

The layout of the machine, in single shear mode, is shown in Figure 6.

The machine consists of a versatile reaction frame (RF) to which are connected three reaction arms (RA) and a shear actuator (SAc). In single shear mode, depicted in Figure 6, the test bearing (TB) together with a multiaxial load cell (MLC) is located between a sliding platen (SP) and a floating platen (FP). A compression actuator (CAc), reacting against hoops (H), forms a caliper for applying a compression force on the test bearing (TB). For simplicity, four auxiliary double-acting actuators in parallel with the compression actuator have been omitted in Figure 6: these are discussed further below.

The design of the reaction frame enables the loads involved with this machine to be self-contained. The main challenge involved with the design of this machine corresponds to the capability of maintaining an angle below 0.003 rad between the loading plates while performing combined axial and shear tests on a single bearing, resulting in a bending moment of up to 1.4MNm, while accommodating a height drop of up to 20mm. The key parts of the reaction frame that required significant stiffness were the arms (RA) that connect the back-frame (RF) (a frame similar to a bi-directional T-Slot bed) to the hoops (H) (a set of two calipers that enables the axial loading system to react against the reaction load of the tested bearing). The longer the arms, the smaller the geometric angle resulting from the rotation of the middle arm. However, it would also reduce the stiffness of the arms in bending. Therefore, a compromise was necessary between length and stiffness.

The main actuator of the axial loading system has a load capacity of 10MN in compression, 1MN in tension and a stroke of 100mm.This actuator is servo-controlled, but also served by a piston accumulator connected to a very large gas reservoir set at the requisite pressure to maintain the correct load on the bearing despite the height drop of the tested sample. This reduces the demand on the servohydraulic system to deliver a high flow of oil, such as it cannot do without a phase error. The piston of the main actuator has the capability to rotate ±1° and is connected to the loading plate by a planar contact. As part of the axial loading system, there is an optional set of four additional double acting actuators, 1MN load capacity and 500mm stroke. These actuators are coupled to each other and the control system enables their use in two different modes:

- Independent mode, which enables the possibility to use them as a crosshead control for setup purposes, longer stroke tension tests or for cyclic tilting tests

- Cross-coupled mode, which gives to the loading plate an additional resistance in tilting. This is very useful when a bearing is tested in combined shear and axial loads.

The shear loading system consists of a Servotest™ double acting actuator, 1MN load capacity and 1m stroke. This actuator is fitted with a 3-stage servo-valve enabling the possibility of performing a cyclic test of ±221mm at 0.1Hz. The hydraulic system is powered by a 600kW Hydraulic power supply, capable of delivering oil at 1000 L/min flow and 280bar.

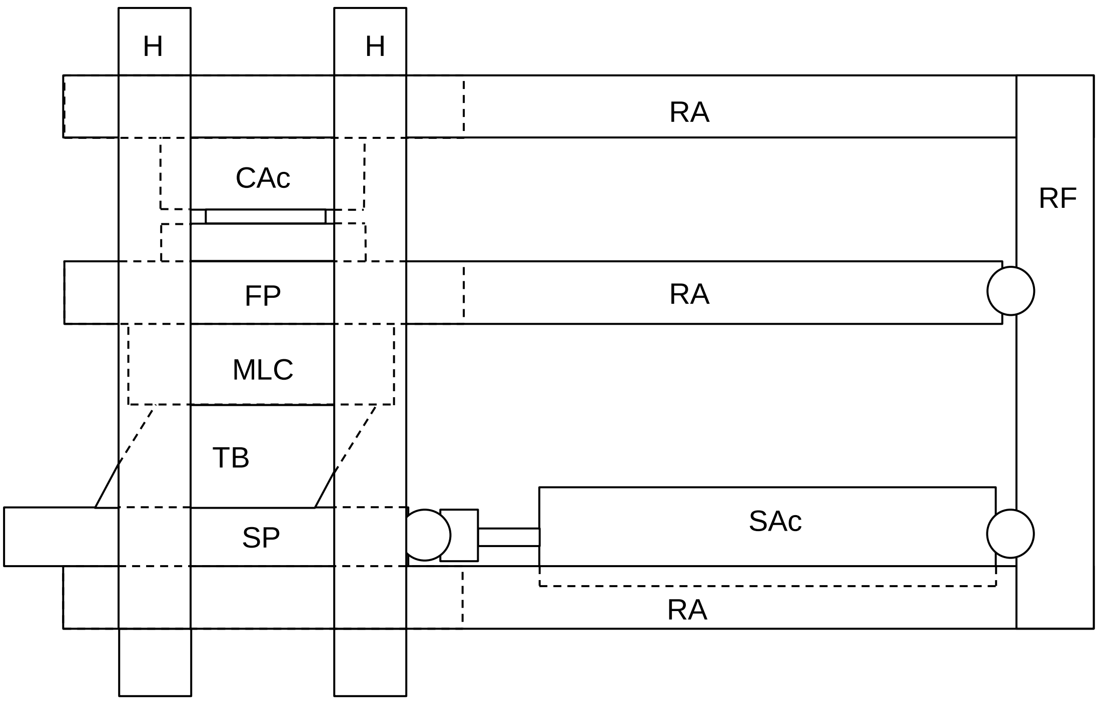

Figure 6 Schematic diagram of plan view of the new testing machine; the structure consists of a reaction frame (RF) connected through two or three reaction arms (RA) to a caliper formed of hoops (H). It enables biaxial loading of a test bearing (TB) using a shear actuator (SAc) and a compression actuator (CAc)

Test	Bearing types	Type test requirements
Capacity in compression under zero lateral displacement	All	Maintain vertical load for at least 3 min whilst examining for signs of failure. Monitor load displacement relation. See 8.2.1.2.6.
Compression stiffness	All	The secant compression stiffness between (1/3) of design load and design load. See 8.2.1.2.8.
Horizontal characteristics under cyclic deformation	All	3rd cycle data for shear strains of ± 5 %, ± 10 %, ± 20 %, ± 50 % and ± 100 % and in 50% increments to above design strain. See 8.2.1.2.2
Horizontal stiffness under a one-sided ramp loading	(Required only if production control test not performed as above)	Measurement of the horizontal secant stiffness under a one-sided ramp loading. See 8.2.1.2.2
Variation of horizontal characteristics with frequency	LRB and PPRB only can be scaled to >500mm	3rd cycle data for shear strain 100% at 0.1 Hz 0.5 Hz 2.0 Hz Other values spaced by the same ratios may be chosen in agreement with the structural engineer. See 8.2.1.2.3
Variation of horizontal characteristics with temperature	LRB and PPRB only, can be scaled to >500mm	3rd cycle data for shear strain 100% over a range of temperatures extending from at least the upper service temperature to at least the lowest service temperature. A test at 23 °C shall be included. Suggested temperatures 40°C, 23°C, 0°C, -10 °C, -20°C. See 8.2.1.2.4
Dependence of horizontal characteristics on repeated cycling	LRB and PPRB only can be scaled to >500mm	1st to 10th cycle data for shear strain of 100 % or the design shear strain if requested by the structural engineer See 8.2.1.2.5
Lateral capacity under maximum and minimum vertical loads	All	Force-displacement curve up to 1.15 * maximum shear displacement or 1.15 * maximum shear load (whichever is reached first) under maximum vertical load and minimum vertical load (may be tensile). Examine for signs of failure. See 8.2.1.2.7.
Creep test under vertical load	If requested by structural engineer	Total creep rate under design vertical load between 10 min and 10^4 min. See 8.2.1.2.10.

Table 1 Tests required by EN15129:2009. LRB = Lead plugged rubber bearing; PPRB =Polymer plugged rubber bearing

Properties		ISO 22762:1 reference	Buildings	Bridges
Compressive properties		6.2.1	Full-scale	Full-scale Optional rotational test
Shear properties		6.2.2	Full-scale	Full-scale
Dependency of shear properties	Shear strain dependency	6.3.1	Full-scale	Scale B
	Compressive stress dependency	6.3.2	Full-scale	Scale B
	Frequency dependency	6.3.3	Material or F-S	Material or F-S
	Repeated load dependency	6.3.4	Full-scale	Scale B
	Temperature dependency	6.3.5	Material or F-S	Material or F-S
Dependence of compressive properties	Shear strain dependency	6.3.6	Optional, Scale B	N/A
	Compressive strain dependency	6.3.7	Optional, Scale B	N/A
Shear displacement capacity		6.4	Scale B	Scale B
Tensile properties		6.5	Optional, Scale B	Optional, Scale B
Durability	Ageing	6.6.1	Material or F-S	Material or F-S
	Creep	6.6.2	Scale A	Scale A
Cyclic compressive fatigue		6.6.3	N/A	Scale B
Reaction force characteristics at low-rate deformation		6.7	N/A	Scale A

Table 2 Tests required by ISO 22762. Scale A bearings are scaled such that diameter ≥150mm or side ≥100mm and rubber layer thickness ≥1.5mm and reinforcing plate thickness ≥0.5mm; Scale B bearings can either be full-scale or scaled such that diameter ≥450mm (500mm for buildings) or side ≥400mm (500mm for buildings) and rubber layer thickness ≥1.5mm and reinforcing plate thickness ≥0.5mm

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