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23 October 2026

Experimental Study on the Friction Behaviour of PTFE Bridge Bearings under In-Service Aging Conditions

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ABSTRACT

The long-term performance of PTFE sliding bearings in bridges is still poorly documented, particularly for devices aged under real service conditions. This study investigates four PTFE bearings removed after 50 years of service from an Italian viaduct in a marine environment. The bearings, originally designed for a maximum vertical load of 2000 kN, were tested up to 2500 kN to evaluate reserve capacity and failure mechanisms. Semi-static and dynamic displacement-controlled tests were performed, with sliding velocities up to 50 mm/s. The results show that, despite visible Teflon degradation and permanent deformation of the steel base plate, the steel–PTFE frictional behaviour remains consistent: the friction coefficient decreases nonlinearly with increasing vertical load and increases with sliding velocity, with the two effects appearing independent. Maximum edge pressures exceeded allowable limits at the highest load level in both loading regimes; however, PTFE extrusion was observed only under dynamic conditions. This indicates that, beyond stress exceedance, speed-related effects, including frictional dissipation and transient reduction of the effective contact area, play a major role in triggering localized extrusion. These findings provide experimental evidence on the behaviour of aged PTFE bearings under realistic conditions and support the assessment and design of existing bridge bearing systems.

KEYWORDS: Bridges; Built environment; Durability-related properties; Friction; Testing, structural elements.

Notation list

α	coefficient of thermal expansion of reinforced concrete
ΔL	longitudinal thermal displacement of the bridge deck
L	span length
ΔT	temperature variation
T_i	initial temperature
T_f	final temperature
F_h	horizontal friction force measured during the test
N	applied vertical load
CoF	Coefficient of Friction

1 Introduction

Polytetrafluoroethylene (PTFE), commonly known as Teflon, is a white thermoplastic material characterized by high chemical stability, weather resistance and an extremely low coefficient of friction (CoF) against steel. The CoF decreases as the applied load increases and as the sliding speed decreases (Campbell, Kong and Manning, 1990; Biswas and Vijayan, 1992; Consiglio Nazionale delle Ricerche, 1998). Owing to these properties, PTFE has been widely used since the early 1960s in the production of bridge support devices (Caltrans, 1994).

In bridge engineering, especially in structures subjected to large temperature variations or heavy vehicle traffic, sliding bearings are required to accommodate deck movements while minimizing the transmission of horizontal forces to the substructure. Given the complexity and cost of replacement, such devices must ensure reliable performance with minimal maintenance throughout their design life.

PTFE sliding bearings are particularly effective in limiting residual horizontal forces transmitted to the bridge substructure. Understanding their long-term behaviour is therefore essential, especially when they are exposed to environmental agents and repeated loading cycles over decades of service.

In European and Canadian practice, unlike in the United States, PTFE bearings are typically dimpled and lubricated with oil. Lubrication further reduces the CoFand limits wear, while the dimples act as lubricant reservoirs, preventing rapid expulsion from the sliding interface (Taylor and Stanton, 2010). Wear of the PTFE layer results from the relative sliding between steel and Teflon and increases with displacement amplitude and surface roughness (Campbell, Kong and Manning, 1990; Marioni, 1983). The presence of lubricant therefore plays a fundamental role in limiting material degradation.

The friction behaviour of PTFE sliding surfaces has been extensively investigated in laboratory studies. Several parameters influence the friction coefficient, including contact pressure, sliding velocity, surface roughness and temperature (Biswas and Vijayan, 1992; Constantinou, Tsopelas and Kasalanati, 1999). Experimental investigations have also shown that sliding velocity and frictional heating may significantly influence wear behaviour, particularly when operating conditions exceed the limits considered in design standards (Quaglini *et al.*, 2010).

In Europe, the design and verification of sliding bearings are regulated by EN 1337 (CEN European Committee for Standardization, 2004), which specifies mechanical requirements, friction limits and testing procedures for structural bearings. In particular, EN 1337-2 provides provisions for sliding elements made of PTFE in contact with stainless steel surfaces, defining allowable pressures and friction limits for design verification.

Despite the large body of experimental work on PTFE sliding surfaces, most available studies are based on laboratory specimens or devices subjected to controlled testing protocols. Experimental evidence on bearings that have experienced natural ageing during several decades of service under real environmental conditions remains relatively limited.

For this reason, the present study investigates the behaviour of PTFE sliding bearings removed after approximately 50 years of service from an Italian viaduct located in a marine environment. Laboratory tests were carried out in order to evaluate their friction behaviour and structural performance under different vertical loads and sliding velocities, with the aim of assessing the residual functionality of these devices after long-term operation.

1.1 Friction behaviour of steel–PTFE sliding interfaces

The friction force between Teflon and steel is the fundamental characteristic of the bearing's function. A fluctuation in the CoF could lead to premature wear of the Teflon pad and to the

transmission of parasitic forces to the substructure, for which the substructure has not been dimensioned.

The CoF depends on several parameters:

- the **contact pressure**, which, as it increases, causes a reduction in CoF;
- the **sliding speed** tends to increase the CoF until a plateau value is reached. Under high sliding velocities, frictional heating may occur at the interface, potentially influencing the tribological behaviour of the PTFE layer (Quaglini *et al.*, 2010);
- the **roughness of the steel plates**, which generally leads to an increase in CoF; roughness may increase further as oxidation and corrosion occur;
- the **temperature**, whose effects are already noticeable at usual levels, increases the CoF when it decreases; below zero CoF (Constantinou, Tsopelas and Kasalanati, 1999) varies drastically, especially in terms of static CoF, which can increase up to 7 times when going from
  $T_i = 20°C$ to $T_f = -35°C$ (Marioni, 1983);
- the **lubrication**, present in the dimples, which further reduces the low CoF, limiting material wear.

The relationship between the CoF and the average pressure on PTFE is provided by EN 1337 for sliding surfaces composed by lubricated PTFE sheets sliding on austenitic steel or aluminium alloy surfaces. This behaviour is also stated by the manufacturer in the technical data sheet for the tested bearings. Figure 1 and Figure 2 summarize the theoretical variation of friction as a function of contact pressure.

Table 11 — Coefficients of friction μ_{max}

Contact pressure σ_p (MPa)	≤ 5	10	20	≥ 30
PTFE dimpled / austenitic steel or hard chromium plating	0,08	0,06	0,04	0,03 (0,025) [a]
PTFE dimpled / aluminium alloy anodized	0,12	0,09	0,06	0,045 (0,038) [a]

[a] These values apply to the frictional resistance of curved sliding surfaces.

Figure 1 Coefficients of friction as function of pressure – extracted from EN 1337

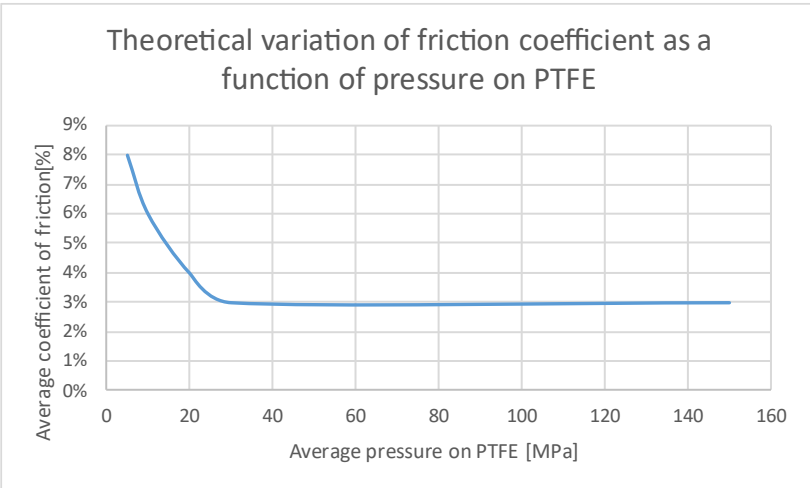

Figure 2 Theoretical variation of friction coefficient as a function of pressure on PTFE

This relationship constitutes the reference framework for the interpretation of the experimental results presented in this study.

1.2 Long-term performance of PTFE

The functionality of steel–PTFE sliding bearings may progressively decrease over time due to the deterioration of the PTFE layer and the modification of the sliding interface. Among the most relevant degradation mechanisms are PTFE extrusion and wear.

Extrusion occurs when a PTFE sheet confined between two steel plates is subjected to compressive stress. Under centrally applied vertical loads, the material expands laterally in a symmetrical manner; under eccentric loading, protrusion becomes more pronounced on the side where pressure is higher. If edge stresses exceed allowable limits, deformation may progress indefinitely, resulting in extrusion (Marioni, 1983) (Figure 3).

Wear, to which PTFE has limited resistance (Biswas and Vijayan, 1992), develops naturally as a result of the displacement cycles experienced by the bearing and increases with sliding speed and vertical load, while it tends to intensify as temperature decreases (Caltrans, 1994; Ala, Power and Azizinamini, 2016b). For this reason, it is essential that the steel sliding surfaces are properly polished, since PTFE wear increases significantly in the presence of surface roughness.

Although the sliding surfaces are generally located within the device and therefore partially protected from oxidation and corrosion, they may still undergo slight surface oxidation, which increases roughness. Surface irregularities may also develop over time due to the accumulation of atmospheric pollutants, leading to minor localized corrosion or point attacks. Moreover, mechanical wear of the steel surfaces, often intensified by the presence of debris or dust, is practically unavoidable. Thermal cycles of expansion and contraction may further generate micro-fractures or local surface variations. In addition, even in the absence of significant external stresses, long-term ageing processes may produce microstructural changes that contribute to an increase in surface roughness.

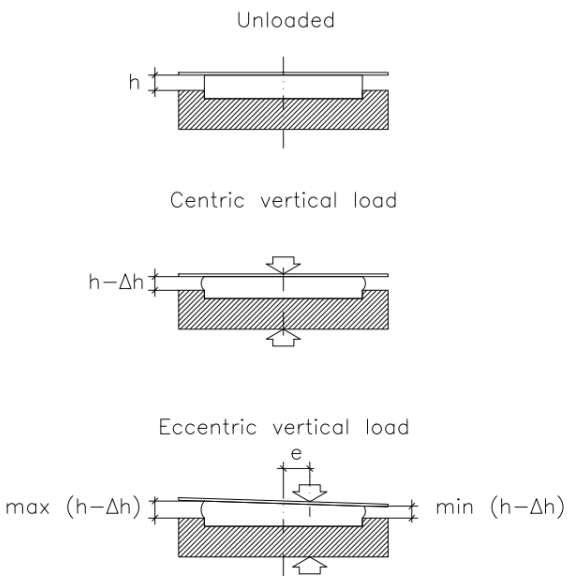

Figure 3 Deformation of PTFE in a sliding support - adapted from "Apparecchi d'appoggio" (Marioni, 1983)

Despite the various degradation mechanisms described above, experimental investigations on bearings that have undergone natural ageing during several decades of service remain

relatively rare. Most available studies are based on laboratory specimens or devices subjected to controlled testing protocols simulating service conditions.

For this reason, experimental evidence obtained from bearings that have operated under real environmental and traffic conditions for extended periods can provide valuable information for assessing their long-term performance. The present study investigates the behaviour of PTFE sliding bearings removed after approximately 50 years of service from an Italian viaduct located in a marine environment.

1.3 State of Art review

Several experimental studies have investigated the frictional behaviour of PTFE sliding bearings, consistently highlighting a strong dependence of the CoF on mechanical and operational parameters. Dorafshan et al. (2019) showed that CoF varies as a function of surface roughness, lubrication conditions, sliding speed, and contact pressure, producing force–displacement hysteretic loops that are qualitatively consistent with those observed in the present study. Moreover, their results indicate that friction tends to decrease with increasing number of displacement cycles, highlighting the importance of loading history on the frictional response, a trend that is also observed in the experimental results presented in this work.

This reduction of friction with cycling is a recurring outcome in the literature. Experimental investigations, including those by Campbell et al. (1990), confirm that the frictional response is strongly dependent on loading history, typically exhibiting an initial transient phase followed by stabilization. In addition, a clear distinction between static (breakaway) and dynamic friction is generally observed, with the latter being lower and evolving consistently with increasing displacement history. Despite differences in testing procedures and boundary conditions, these trends are consistently reported across independent experimental studies. More recent experimental programs, such as that conducted by Nejad and McGormley (2024), further confirm these findings, highlighting that the CoF is strongly influenced by contact pressure, sliding velocity, surface contamination, and PTFE typology. In particular, their results show that friction decreases with increasing contact pressure, while it increases with sliding speed and contamination. Surface contamination was found to have a particularly significant effect, with even light dust leading to a substantial increase in friction, and severe contamination potentially preventing sliding altogether. Furthermore, once elevated due to high loading rates, friction values do not decrease, suggesting irreversible modifications of the PTFE surface caused by thermal and mechanical effects.

The influence of temperature has also been investigated, particularly by Constantinou et al. (1999) who reported a decrease in friction with increasing temperature based on tests conducted in the range between −60°C and 20°C. Although these experiments were not extended to very high temperatures, they nevertheless capture the general trend of frictional behaviour, indicating that thermal effects play a significant role in the response of PTFE sliding interfaces.

From a design perspective, Quaglini et al. (2010) highlighted that current standards, such as EN 1337, are largely based on experimental datasets developed in the 1970s and 1980s, and may not fully represent the behaviour of PTFE bearings under modern operating conditions. In particular, the combined effects of high sliding velocities and elevated temperatures are not adequately addressed, despite their potential impact on both friction and durability.

The long-term performance of PTFE bearings is strongly influenced by wear mechanisms, as discussed in studies on high-load multi-rotational bridge bearings by Stanton, Roeder, and Campbell (1999). Wear of PTFE depends on several parameters, including contact pressure, temperature, lubrication, sliding speed, and accumulated sliding distance, which are also the primary factors governing friction. Experimental observations indicate that wear processes

are complex and involve material transfer, formation of debris and flakes, and possible delamination at the molecular level. Sliding speed has been identified as a dominant parameter, with higher speeds leading to increased wear rates, while lubricated or filled PTFE generally shows improved performance compared to unfilled materials.
The effect of loading history and displacement demand has also been investigated under seismic conditions. Experimental investigations by LaFave et al. (2013) showed that the CoF of PTFE bearings increases significantly with slip rate during seismic events. While quasi-static tests typically yield friction coefficients lower than 0.07, dynamic loading representative of earthquake conditions can lead to values in the range of 0.15–0.18. These results were obtained by imposing displacement histories derived from recorded seismic events, characterized by significantly higher amplitudes compared to standard laboratory protocols, reaching approximately 250 mm in the longitudinal direction and about 180–200 mm in the transverse direction. This highlights the limitations of conventional quasi-static testing in capturing the actual behaviour of bearings under extreme loading conditions, in agreement with the observations reported by Quaglini. Similarly, studies by Konstantinidis, Kelly, and Makris (2008) showed that friction evolves with cumulative displacement, typically decreasing during sliding. In particular, the hysteretic response is characterized by a force overshoot at the onset of motion, followed by a progressive reduction in force attributed to heat generation at the sliding interface and variations in instantaneous sliding velocity.
Overall, despite differences in experimental setups and bearing typologies, the literature provides a consistent and coherent picture of PTFE frictional behaviour, characterized by non-linear and path-dependent response, as well as a progressive evolution of friction with cyclic loading, sliding velocity, and displacement history. However, it is important to emphasize that most available results are derived from laboratory tests on new specimens, which do not fully reproduce the cumulative displacement demand and environmental exposure experienced by bearings in real structures over their service life. In contrast, bridge bearings in real structures are subjected to long-term cumulative displacements, environmental exposure, and aging effects, which may significantly alter their frictional response. This limitation represents a key gap in the current state of knowledge and motivates the present study, which focuses on the behaviour of existing bearings subjected to real in-service conditions.

2 Experimental programme

2.1 Tested bearings

Laboratory tests were carried out on four support devices removed from an Italian viaduct located near Genoa, approximately 6 km from the coastline. The bridge was constructed in 1975, and the bearings were originally manufactured by ALGA S.p.A., an Italian company specialised in bridge bearing systems.

The viaduct consists of a girder deck with three spans, each approximately 40 m long, supported by four post-tensioned prestressed concrete (PTC) beams (Figure 4). The deck has

a total width of approximately 13 m, and the beams rest on single-shaft piers with a maximum height of about 25 m.

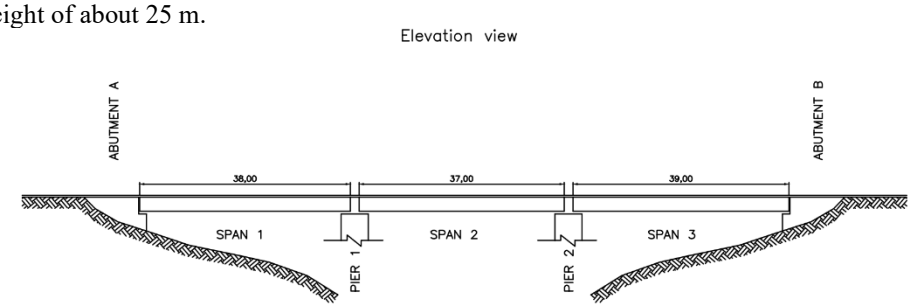

Figure 4 Bridge elevation view

The bearings analysed can be classified into two categories:

- **Multidirectional** (no. 1 and no. 2):
  The upper plate of the bearing is equipped with a Teflon bearing that facilitates relative sliding with the lower plate (Figure 5).
  Displacements were permitted parallel and transverse to the axis of the bridge.
  The geometry and dimensions of the PTFE pads are shown in Figure 6.

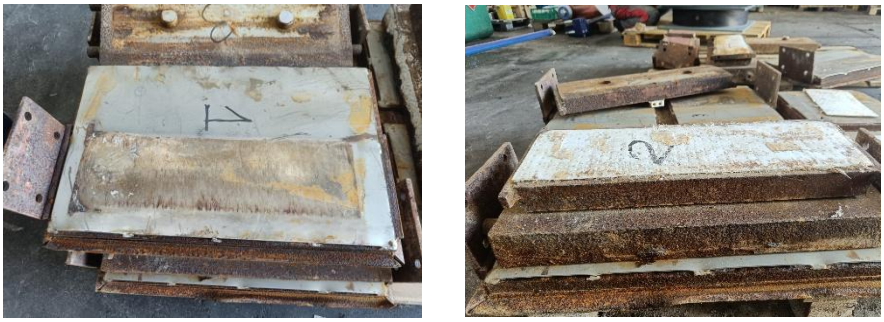

Figure 5 Multi-directional Teflon bearing - lower plate (left) and upper plate with Teflon sheet (right)

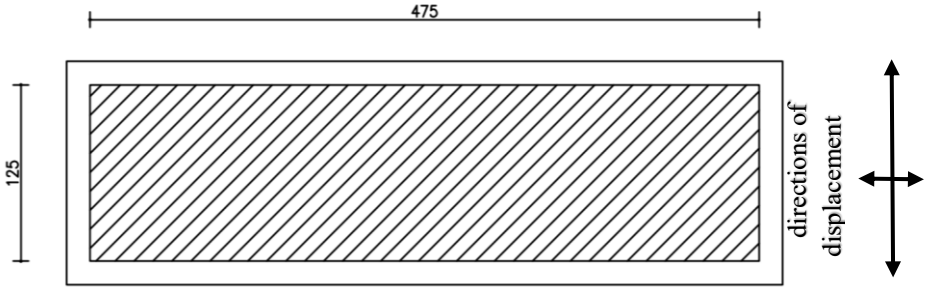

Figure 6 PTFE pads dimensions (in mm) - Multidirectional bearings

- **Unidirectional** (No. 3 and No. 4):
  They are equipped with a guide that allows displacement only in a direction parallel to the longitudinal axis of the viaduct. The guide is realised by means of a groove in the lower plate that matches a notch in the upper plate, which is equipped with two Teflon pads.

The unidirectional bearing configuration is shown in Figure 7. The dimensions of the PTFE pads for the unidirectional bearings are shown in Figure 8.

Figure 7 Unidirectional Teflon bearing - upper (left) and lower (right) plates

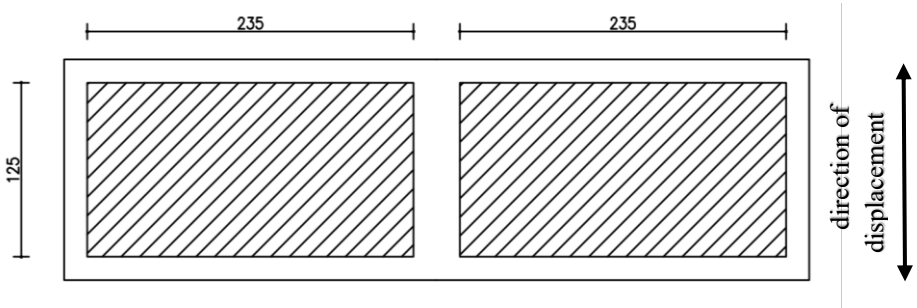

Figure 8 PTFE pads dimensions (in mm) - Unidirectional bearings

The PTFE sliding sheets are provided with a dimple pattern intended to retain lubricant within the sliding interface. The spacing of the dimples is approximately 13.5 mm in one direction and 15 mm in the orthogonal direction. Although the bearings predate the current European standards, this geometry is consistent with the requirements specified in EN 1337 for PTFE sliding elements.

Both types of bearings were originally designed for a maximum vertical load of approximately **200 tonnes (≈ 2000 kN)**. At the time of construction (1975), the design of sliding bearings in Italy was typically performed according to the CNR recommendations, which predate the adoption of the modern ultimate limit state (ULS) design approach currently used in European standards.

The bearings were designed with a maximum longitudinal displacement capacity of 17.5 cm. This value refers to the geometric displacement capacity of the devices and does not necessarily correspond to the actual movements experienced by the bridge during service. Since the original bridge design documentation was not available, the reasons that led to the adoption of such displacement capacity could not be verified.

In order to estimate the order of magnitude of the longitudinal movements that may occur during service, the thermal expansion of the bridge deck can be considered. For the area of Genoa, the minimum winter air temperature is approximately −10 °C, while the maximum summer air temperature reaches approximately 40 °C. For structural elements particularly sensitive to thermal actions, such as bearings and expansion joints, design provisions generally consider additional temperature margins (±20 °C) with respect to air temperature.

Assuming an initial reference temperature of 15 °C, the resulting maximum temperature variation may be estimated as $\Delta T \approx 41$ °C. Assuming a typical coefficient of thermal expansion for reinforced concrete of approximately $\alpha = 10^{-5}$ °C^{-1}, the longitudinal displacement of a span of approximately 38–40 m can be estimated as

$$\Delta L = \alpha L \Delta T \qquad \text{(Eq. 1)}$$

which results in longitudinal movements of approximately 15–20 mm due to thermal effects alone.

This estimate neglects additional displacement contributions due to shrinkage of concrete, braking forces or seismic actions. These values confirm that the displacement capacity of the tested bearings (17.5 cm) is significantly larger than the movements expected from thermal effects alone.

2.2 Degradation level of bearings

The condition of the bearings was visually inspected prior to the laboratory testing in order to assess the level of degradation after approximately 50 years of service.

The external surfaces of the devices show evident signs of corrosion, with a rust layer covering most of the exposed steel components. This condition is consistent with the environmental exposure of the viaduct, which is located approximately 6 km from the coastline.

Some construction details of the steel components are also visible. In particular, the connection between steel plates is realized through localized welding spots along the perimeter, as shown in Figure 9. In some locations, the detachment of some welds is visible.

The PTFE pads exhibit visible signs of ageing and surface deterioration (Figure 10). Local irregularities and partial material degradation can be observed, although the sliding surfaces remain generally intact, with no major loss of material observed prior to testing.

A significant feature observed in the multidirectional bearings is the permanent deformation of the stainless-steel sliding plate of the lower element. As shown in Figure 11, a clear imprint of the upper plate is visible on the lower plate. This deformation suggests that the bearing may have remained in a relatively fixed position during a significant portion of its service life, resulting in sustained compressive stresses acting on the same contact area. This condition may also be related to the relatively large displacement capacity originally provided for the bearings compared with the movements expected from thermal effects alone.

In order to evaluate the residual behaviour of the devices in conditions representative of their actual in-service state, no extraordinary cleaning, lubrication or restoration operations were performed prior to testing. The only operation carried out consisted of removing superficial corrosion products from the outer surfaces of the plates, without affecting the sliding interface.

For the multidirectional bearings in particular, the permanent deformation of the lower plate may influence the contact conditions between the steel and PTFE surfaces during testing. This aspect should therefore be considered when interpreting the experimental results presented in the following sections.

Figure 9 Incomplete welding of the steel plates

Figure 10 Degradation of Teflon pads

Figure 11 Deformation of the steel plate in multidirectional bearing

2.3 Testing Methodology

The laboratory tests were carried out at the **Sismalab Anti-Seismic Devices Test Laboratory (Italy)** using a hydraulic testing machine designed for the characterization of structural bearings and seismic isolation devices (Figure 12).

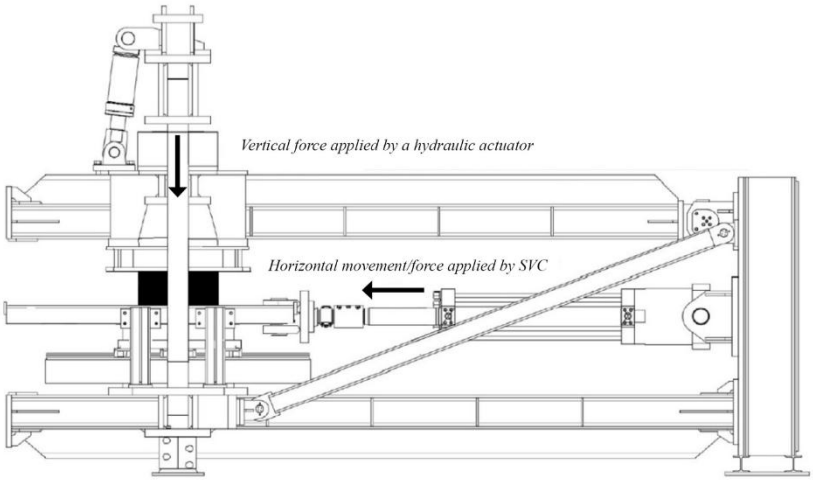

Figure 12 Testing machine

The testing system allows the application of controlled vertical loads up to approximately 5000 kN and horizontal loads up to about 1350 kN, with a maximum actuator stroke of approximately ±450–500 mm and a maximum sliding velocity of about 0.8–0.9 m/s.

During the tests, a constant vertical load was applied to the specimen through a hydraulic actuator controlled by pressure transducers. Horizontal movement was imposed by a second hydraulic actuator operating in displacement control.

The horizontal force developed during sliding was measured through a load cell positioned between the actuator and the specimen, while the horizontal displacement was monitored using a position transducer located near the piston rod. The applied vertical load was monitored through the testing system control instrumentation.

All signals from the transducers were recorded and processed through the Sisma-Control data acquisition system with a sampling frequency of 200 Hz (sample time 5 ms), ensuring adequate resolution for the imposed displacement histories.

The tests were conducted at an ambient laboratory temperature of approximately 20 °C, which was not actively controlled during the experimental campaign.

The CoF between the PTFE and steel sliding surfaces was evaluated as:

$$CoF = \frac{F_h}{N} \qquad \text{(Eq. 2)}$$

where F_h is the measured horizontal force and N is the applied vertical load.

The friction contribution of the testing apparatus was automatically compensated by the data processing system during signal processing, so that the reported horizontal forces correspond to the effective friction at the steel–PTFE sliding interface.

Two sets of tests were carried out for both types of bearings:

- **Semistatic tests** were performed with a pre-loading stage for the first load step, in order to simulate slow displacements of the bearings during service conditions. A maximum displacement of approximately ±6 mm was imposed at a velocity of 0.1 mm/s, as shown in Figure 13, in order to investigate the variation of the friction coefficient and the overall behaviour of the support as a function of the applied vertical load.

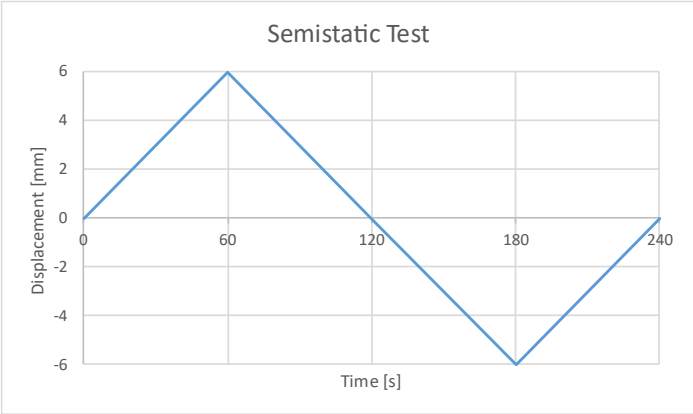

Figure 13 Displacement imposed over time on bearings for semi-static tests

The test was repeated for the following vertical loads:

- **1700 kN**;
- **2000 kN**;
- **2500 kN**.

The preload for the first load step (1700 kN) lasted 30 minutes.

- **Dynamic tests** were carried out for the same vertical loads adopted in the semi-static tests, with imposed displacements of approximately ±45 mm at sliding velocities of 10 mm/s and 50 mm/s, in order to investigate the variation of the friction coefficient as a function of sliding velocity and vertical load. For each test configuration, three complete displacement cycles were applied, as shown in Figure 14. The adopted displacement amplitude is larger than the movements expected from thermal effects alone (approximately 20 mm for the investigated bridge), but it allows more severe operating conditions to be explored, including the combined effects of temperature variations, long-term structural deformations and exceptional loading conditions such as seismic actions.

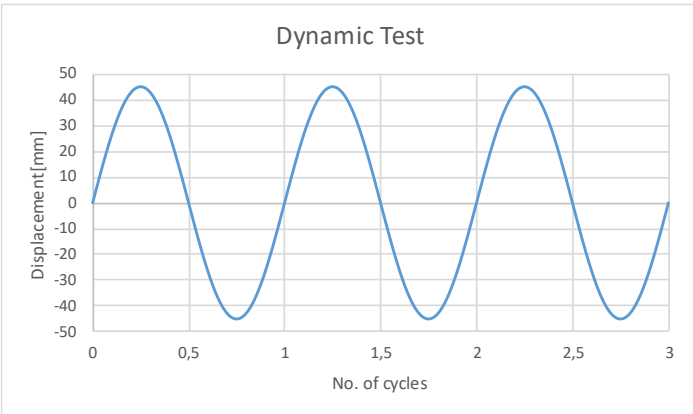

Figure 14 Cycles of displacements imposed on bearings for dynamic tests

To summarise, six semi-static and twelve dynamic tests were carried out, as shown in Table 1. The detailed results of the experimental tests are reported in ANNEX A – Tests Results. It should be noted that the experimental program did not aim to evaluate the

horizontal resistance capacity of the bearings. The horizontal actuator was used only to impose controlled sliding displacements along the permitted directions of movement of the devices.

Table 1 Tests conducted on bearings

Semistatic tests				
Bearing type [-]	**Vertical load [kN]**	**Pre-load [min]**	**Max displacement [mm]**	**Min. displacement [mm]**
Multidir.	1700	30	5.5	-5.7
	2000	0	5.7	-5.7
	2500	0	5.6	-5.7
Unidir.	1700	30	5.7	-5.7
	2000	0	5.9	-5.8
	2500	0	5.9	-5.8
Dynamic tests				
Bearing type [-]	**Vertical load [kN]**	**Speed [min]**	**Max. displacement [mm]**	**Min. displacement [mm]**
Multidir.	1700	10	44.7	-44.6
	1700	50	44.3	-44.3
	2000	10	44.6	-44.7
	2000	50	44.2	-44.3
	2500	10	44.4	-44.7
	2500	50	44.1	-44.3
Unidir.	1700	10	44.7	-44.6
	1700	50	44.1	-44.2
	2000	10	44.3	-44.6
	2000	50	44	-44.2
	2500	10	44.1	-44.5
	2500	50	43.8	-44.2

The compressive stresses acting on the PTFE sliding surfaces depend on the magnitude of the applied vertical load. In order to evaluate these stresses during the experimental program, the contact pressure on the PTFE (Table 2) was calculated according to the provisions of **EN 1337-2**, shown in Figure 15.

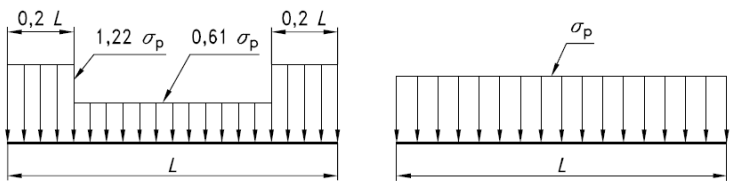

Figure 15 Alternative PTFE pressure distributions – extracted from EN-1337-2

Table 2 Pressure on PTFE during tests

Bearing type [-]	Vertical load [kN]	Average pressure [MPa]	Maximum edge pressure [MPa]
Unidir.	1700	29	35
	2000	34	42
	2500	43	52
Multidir.	1700	29	35
	2000	34	41
	2500	42	51

The CNR 10018-85 (Consiglio Nazionale delle Ricerche, 1985) standard provides guidance on the maximum permissible compressive pressures on PTFE, as shown in the extract below.

"Table V shows the allowable pressures on PTFE surfaces. The PTFE surfaces are calculated without deducting the areas occupied by lubrication imprints.
When evaluating pressures on PTFE, in addition to vertical loads, the following factors — considered in the most unfavorable combination — must also be taken into account:

- *parasitic moment due to rotation;*
- *torsional moment in case rotation around a given axis is hindered;*
- *the effect of horizontal forces in the case of fixed or unidirectional supports.*

The allowable compressive pressures specified by CNR 10018-85 are reported in Table 3.

Table 3 CNR 10018-85 Table V - Permissible pressures on PTFE

Load type	Maximum average pressure [MPa]		Maximum edge pressure [MPa]	
	Bonded PTFE	Embedded PTFE	Bonded PTFE	Embedded PTFE
Permanent	20	30	25	35
Total	30	45	35	50

According to the CNR 10018-85 recommendations, the allowable compressive pressures on PTFE depend on the installation configuration of the sliding sheet. In the present case, the bearings are characterized by embedded PTFE pads, for which the maximum allowable edge pressure under total loads is 50 MPa.

For the load levels considered in the experimental programme, the calculated pressures remain within this limit for vertical loads of 1700 kN and 2000 kN. For the highest load level (2500 kN), the calculated edge pressure slightly exceeds the CNR limit, reaching 52 MPa for the unidirectional bearing and 51 MPa for the multidirectional bearing.

Although EN 1337-2 provides characteristic compressive strengths for sliding materials (e.g. 90 MPa for PTFE sliding surfaces under variable loads), these values refer to new materials and are intended for design verification within the framework of modern limit-state approaches. In the present study, the comparison with allowable pressures was therefore performed with reference to the CNR recommendations, which provide more conservative limits and were also closer to the design practice adopted at the time of construction of the investigated bearings.

3 Discussion of findings

3.1 General considerations

The interpretation of the experimental results was carried out by comparing the behaviour of the tested bearings with the theoretical and experimental friction trends reported in the literature and in design standards for steel–PTFE sliding interfaces. In particular, the measured friction behaviour was evaluated with respect to the relationships between friction coefficient, contact pressure and sliding velocity typically observed for intact PTFE bearings. Since new bearings identical to the tested devices were not available, a direct comparison with the behaviour of unused bearings could not be carried out.

Overall, the experimental results show that the friction behaviour of the aged bearings remains consistent with the trends commonly reported in the literature for steel–PTFE sliding interfaces. In particular, the CoF decreases with increasing contact pressure and increases with sliding velocity.

These trends were observed for both multidirectional and unidirectional bearings and remain identifiable despite the visible degradation of the devices and their long service life of approximately 50 years.

In the force–displacement diagrams obtained during the tests, a progressive reduction of the horizontal force within the same loading cycle can often be observed. This behaviour is likely related to frictional heating occurring at the sliding interface, which may reduce the CoF as the PTFE temperature increases during repeated sliding, as also observed by Nejad and McGormley (2024).

It is also worth noting that the bearings were tested under vertical loads up to 2500 kN, which slightly exceeds the original design load of approximately 2000 kN. Despite the visible degradation of the devices and the permanent deformation observed in the steel base plates, no structural failure of the bearing assembly was observed during the performed tests.

3.2 Semistatic tests

The results obtained from the semistatic tests confirm the expected dependence of the friction coefficient on the applied vertical load. The average friction coefficients measured during the tests are summarized in Table 4. For both bearing types, friction decreases from values of approximately 4–5% at lower pressures to about 2–3% at the highest pressure level.

Table 4 Reduction of friction as vertical load increases

Semistatic tests			
Bearing type [-]	**Vertical load [kN]**	**Average pressure PTFE [MPa]**	**Average friction [%]**
Multidir.	1700	29	4.6%
	2000	34	3.5%
	2500	42	3.0%
Unidir.	1700	29	3.5%
	2000	34	2.6%
	2500	43	2.3%

This behaviour is consistent with the well-established relationship between friction and contact pressure for steel–PTFE sliding interfaces reported in the literature and in design recommendations (Consiglio Nazionale delle Ricerche, 1985; Campbell, Kong and Manning, 1990; Biswas and Vijayan, 1992).

A comparison between the theoretical friction values provided by the standards (Figure 2) and the experimental results shows a generally good agreement, as illustrated in Figure 16. In particular, the friction coefficient follows a nonlinear decreasing trend as the average pressure acting on the PTFE increases.

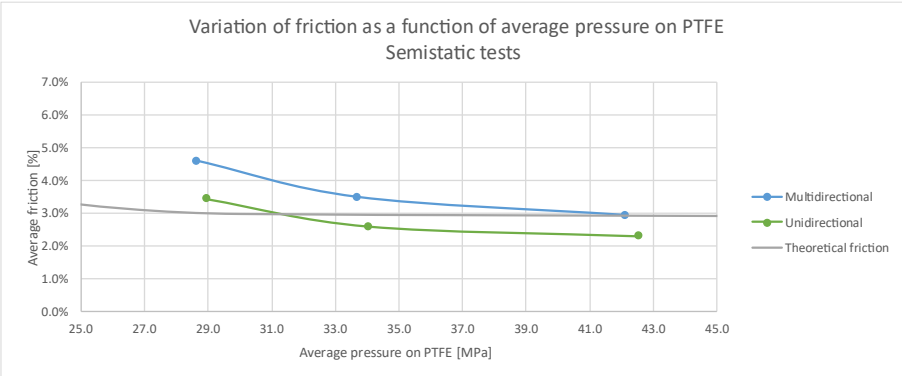

Figure 16 Variation of friction as a function of average pressure on PTFE

As shown in Figure 16, the friction coefficients measured for the multidirectional bearings are consistently higher than the theoretical maximum values indicated by the reference curve. Conversely, for the unidirectional bearings the measured friction exceeds the theoretical value only at the lowest load level (1700 kN), while at higher pressures the experimental values remain close to or below the theoretical prediction.

The preload tests performed at the load level of 1700 kN also allowed the static friction coefficient to be estimated. The measured static friction values are approximately twice the corresponding dynamic friction values for both types of bearings, as shown in Table 5. This behaviour is consistent with the typical tribological behaviour of PTFE sliding interfaces reported in previous experimental studies.

Table 5 Variation of friction from static to dynamic conditions

Semistatic tests			
Bearing type [-]	**Static friction [%]**	**Average dynamic friction [%]**	**Static/dynamic friction [-]**
Multidir.	10.6%	4.6%	2.3
Unidir.	6.6%	3.5%	1.9

It should also be noted that the calculated edge pressure slightly exceeded the limit specified by CNR 10018-85 for embedded PTFE pads (50 MPa) at the highest load level of 2500 kN.

Despite this exceedance, no visible damage or extrusion of the PTFE layer was observed during the semistatic tests. This behaviour is likely related to the relatively small imposed displacements (approximately ±6 mm), which limited the sliding demand on the PTFE surface even under compressive stresses slightly higher than the allowable values.

3.3 Dynamic tests

The dynamic tests confirm that the sliding velocity significantly influences the friction behaviour of the steel–PTFE interface. This trend is consistent with the behaviour previously reported in the literature for intact bearings (Campbell, Kong and Manning, 1990; Biswas and Vijayan, 1992; Taylor and Stanton, 2010; Dorafshan *et al.*, 2019).

For both multidirectional and unidirectional bearings, the CoF increases as the sliding velocity increases. This behaviour is observed consistently for all the investigated vertical load levels.

Since the dynamic tests were carried out for different vertical loads (1700 kN, 2000 kN and 2500 kN), it is possible to evaluate the combined influence of vertical pressure and sliding velocity. The results show that, although the friction coefficient decreases with increasing vertical load, the increase in friction associated with higher sliding velocities remains approximately constant for all load levels.

This behaviour is visible in Figure 17, where the curves representing the variation of friction as a function of sliding speed for different vertical loads appear approximately parallel. This indicates that the effect of sliding velocity on the friction coefficient is largely independent of the applied vertical load.

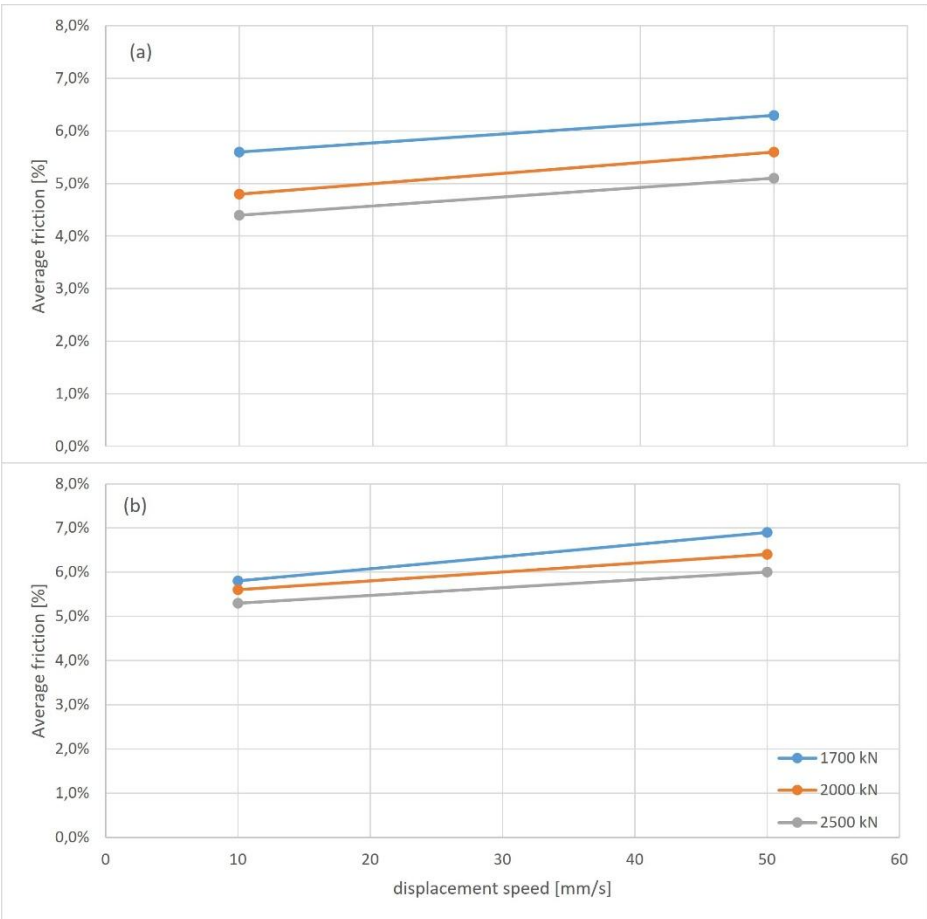

Figure 17 Variation of friction as a function of displacement speed (for multiple applied vertical loads) – (a) Multidirectional and (b) Unidirectional bearings

The linear relationships between sliding velocity and friction coefficient were evaluated for the different test configurations and are summarised in Table 6. The calculated slopes show an average increase in friction of approximately 0.02% per mm/s of sliding velocity, while the intercept varies depending on the applied vertical load.

Table 6 Calculation of linear relationships between sliding speed and coefficient of friction

Dynamic test						
Bearing type [-]	**Vertical Load [kN]**	**Speed [mm/s]**	**Average friction [-]**	**Increase in friction [%]**	**Interpolating line gradient [%]**	**Y-Intercept value [%]**
Multidir.	1700	10 50	5.60% 6.30%	0.70%	0.0175%	5.425%
Multidir.	2000	10 50	4.80% 5.60%	0.80%	0.0200%	4.600%
Multidir.	2500	10 50	4.40% 5.10%	0.70%	0.0175%	4.225%
Unidir.	1700	10 50	5.80% 6.90%	1.10%	0.0275%	5.525%
Unidir.	2000	10 50	5.60% 6.40%	0.80%	0.0200%	5.400%
Unidir.	2500	10 50	5.30% 6.00%	0.70%	0.0175%	5.125%
			Average value	0.80%	0.0200%	5.050%

Focusing again on the influence of the pressure acting on the PTFE layer, Figure 18 presents the variation of the friction coefficient as a function of the average pressure on PTFE for the different sliding velocities and bearing types.

The curves shown in Figure 18 highlight that increasing the sliding velocity results in an approximately uniform upward shift of the friction–pressure relationship. In other words, while the general decreasing trend of friction with increasing pressure is maintained, higher sliding velocities lead to consistently higher friction values.

These observations indicate that the influence of sliding velocity and the influence of vertical pressure on friction can be considered largely independent within the investigated range of parameters.

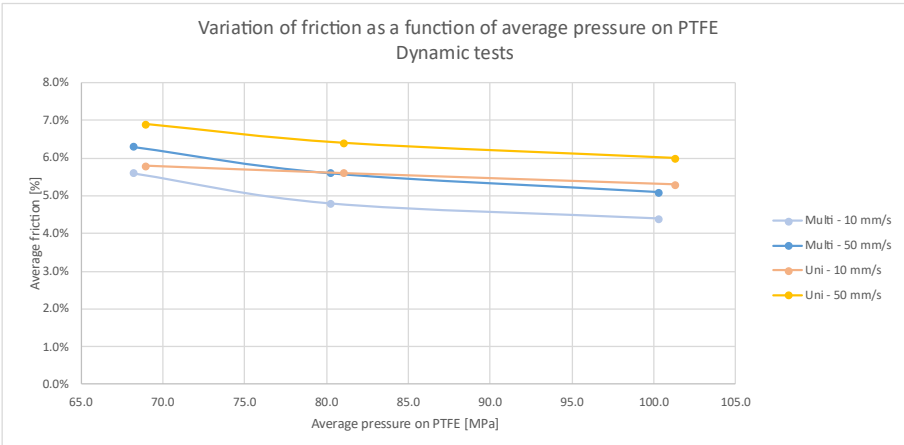

Figure 18 Variation of friction as a function of average pressure on PTFE in dynamic tests

A relevant observation concerns the physical condition of the PTFE pads after the dynamic tests. Unlike the semistatic tests, where no visible damage was observed, the dynamic tests

resulted in local extrusion of the PTFE material at the edges of the sliding surface (Figure 19).

This phenomenon cannot be explained solely by the increase in compressive stress acting on the PTFE. In fact, although the edge pressure slightly exceeded the recommended limit for embedded PTFE pads only at the highest load level (2500 kN), no damage was observed during the semistatic tests under similar compressive stresses.

The observed extrusion is therefore likely related to the combined effect of larger sliding displacements and higher sliding velocities, which increase the frictional energy dissipated at the sliding interface (Table 7). Under dynamic conditions, the pressure distribution within the PTFE layer may also require some time to stabilize, potentially leading to a temporary reduction of the effective contact area and to locally higher stresses at the edges of the sliding surface.

Table 7 Dissipated Energy measured during tests

Test Type	Vertical Load [kN]	Sliding speed [mm/s]	Dissipated Energy [J] Multidir.	Unidir.
Semistatic	1700	-	1746	1370
	2000	-	1600	1220
	2500	-	1660	1356
Dynamic	1700	10	17071	17610
	2000	10	17056	19826
	2500	10	19390	23509
	1700	50	19178	20668
	2000	50	19980	22546
	2500	50	22537	26173

Figure 19 PTFE outflow in the unidirectional bearing after the test

Furthermore, it can be observed in Figure 20 that the sliding of the Teflon left some lubricant on the steel plate, as already evidenced in the tests carried out by Ala et al. (2016a) on intact bearings, which was therefore still present inside the dimples of the PTFE layer, confirming the effectiveness of their function. However, it is not only the lubricant that is present on the plates but also the Teflon itself, which is almost completely worn away at the end of the tests, compromising the functionality of the device for subsequent use.

Figure 20 Presence of lubricant on the steel plate as a result of PTFE sliding – unidirectional (left) and multidirectional (right) bearing

4 Conclusions

This study investigated the friction behaviour and residual performance of PTFE sliding bearings removed after approximately 50 years of service from a bridge located in a marine environment. Laboratory tests were performed under semi-static and dynamic loading conditions in order to evaluate the influence of vertical load and sliding velocity on the friction behaviour of the steel–PTFE interface.

Despite the visible degradation of the devices and the permanent deformation observed in the steel base plates, the fundamental friction behaviour of the steel–PTFE interface remained consistent with the trends commonly reported in the literature for intact bearings. In particular, the CoF decreases with increasing vertical load and increases with sliding velocity. The experimental results also indicate that the effects of sliding velocity and vertical load on the friction coefficient can be considered largely independent within the investigated range of parameters.

During the semi-static tests, no visible damage to the PTFE sliding surfaces was observed, even when the compressive stresses slightly exceeded the allowable limits specified by the CNR recommendations for embedded PTFE pads. This behaviour can likely be attributed to the relatively small imposed displacements, which limited the sliding demand on the PTFE layer.

Conversely, during the dynamic tests, local extrusion of the PTFE material was observed at the edges of the sliding surfaces. This phenomenon appears to be associated with the combined effects of larger sliding displacements and higher sliding velocities, which increase the frictional energy dissipated at the sliding interface and may lead to localized stress concentrations.

The results suggest that, even after decades of service and in the presence of visible degradation of the steel components, the tribological behaviour of the steel–PTFE interface can remain largely preserved. However, under more severe sliding conditions, significant PTFE extrusion and wear may occur, potentially compromising the long-term functionality of the device.

These findings contribute to the limited body of experimental evidence available on naturally aged bridge bearings and provide useful indications for the assessment and maintenance of existing bridge infrastructure, particularly where inspection data are limited and replacement decisions must rely on indirect evidence of performance.

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ANNEX A – Tests Results

In the force–displacement diagrams reported in this annex, the orange curve represents the friction of the testing apparatus. This contribution was evaluated during the tests and subtracted from the raw measurements during data processing, so that the reported results correspond to the net friction force at the steel–PTFE sliding interface. The complete force–displacement diagrams obtained during the experimental campaign are reported in this annex in order to provide full documentation of the experimental results and allow direct inspection of the raw test behaviour.

A.1 Semistatic tests

The semistatic tests were carried out under displacement control with a maximum imposed displacement of approximately ±6 mm. The force–displacement diagrams obtained for the different vertical load levels and bearing types are reported in Figure 21 through Figure 26.

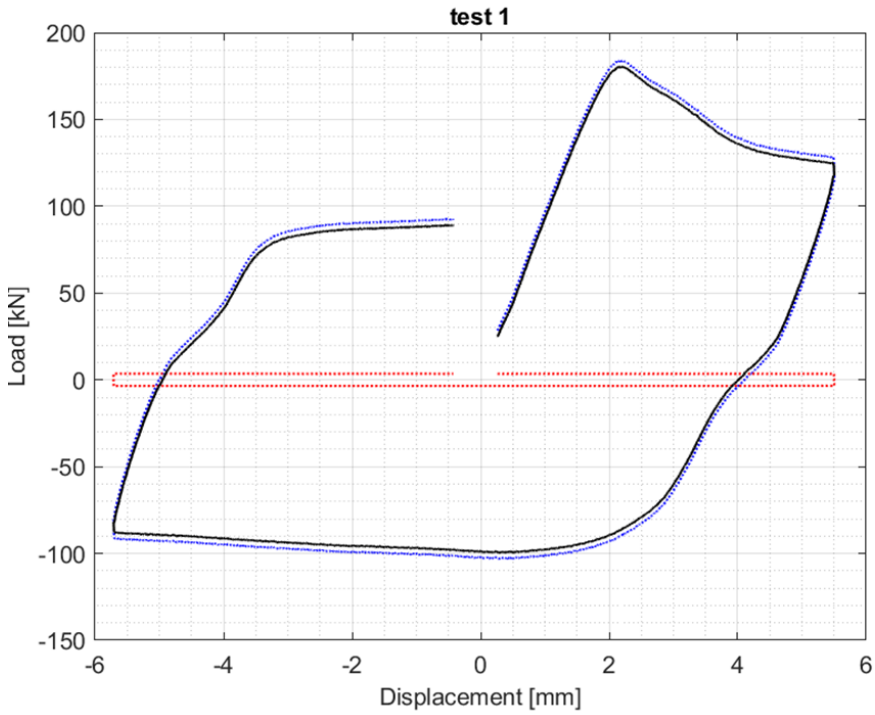

Figure 21 Semistatic test – multidirectional bearing – N = 1700 kN

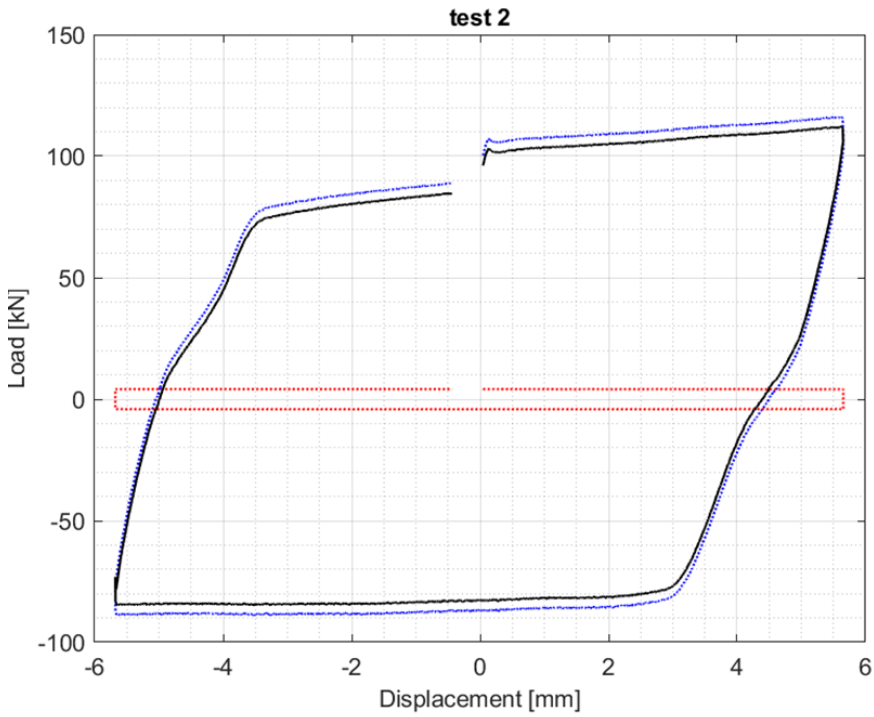

Figure 22 Semistatic test – multidirectional bearing – N = 2000 kN

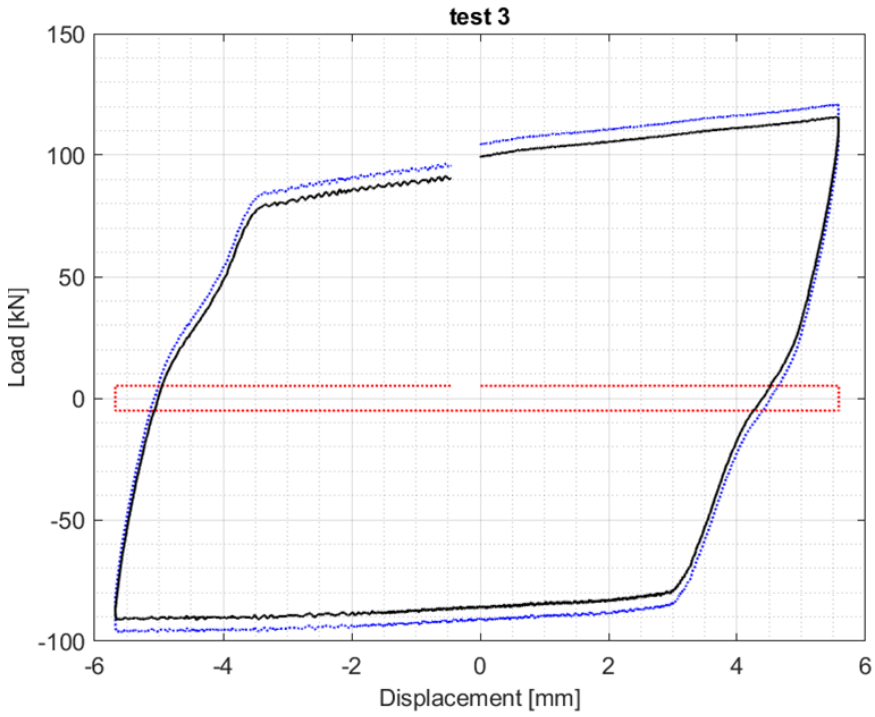

Figure 23 Semistatic test – multidirectional bearing – N = 2500 kN

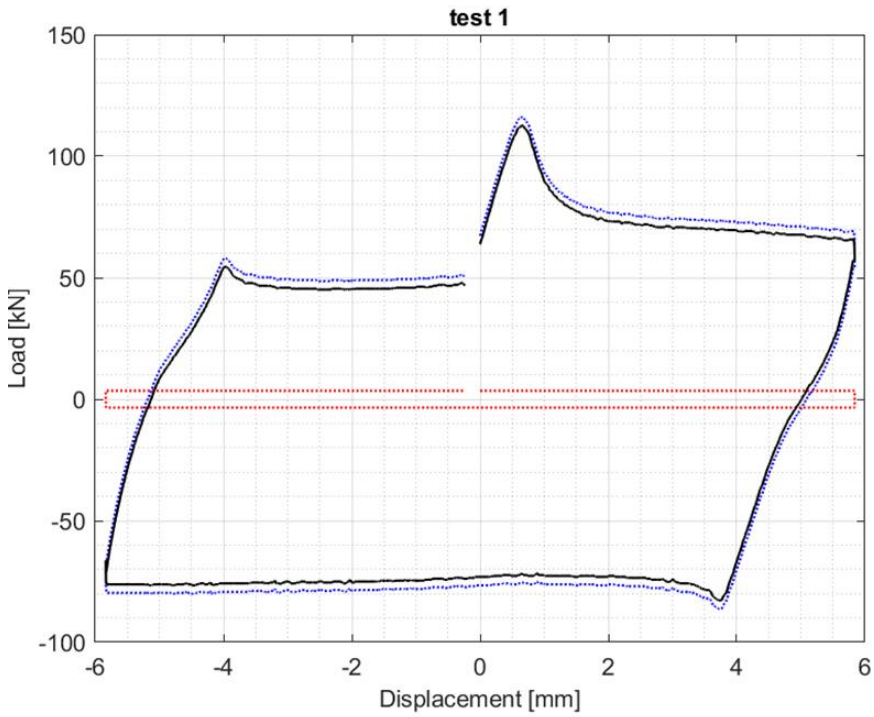

Figure 24 Semistatic test – unidirectional bearing – N = 1700 kN

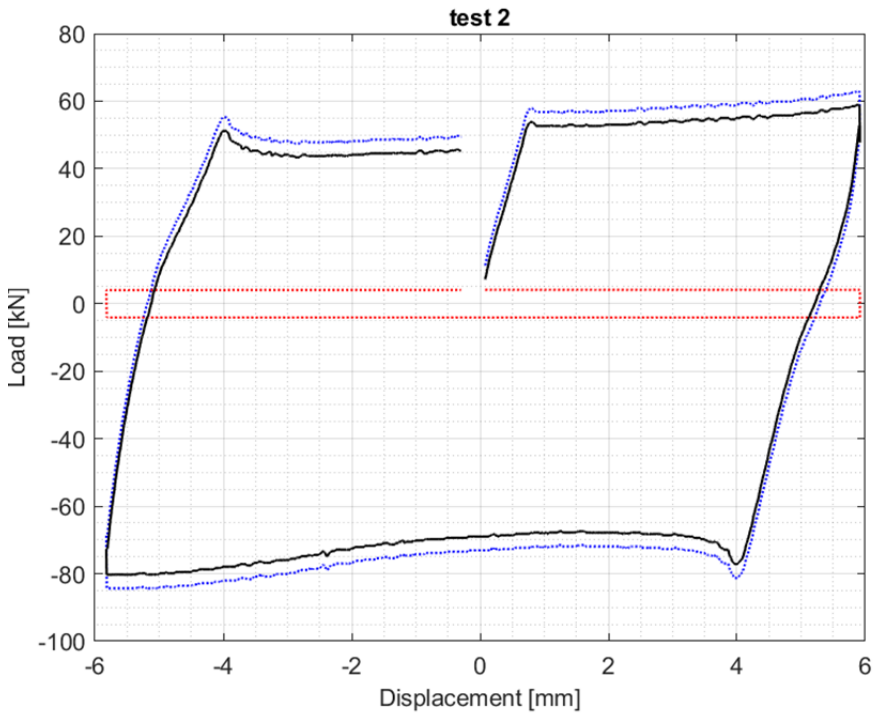

Figure 25 Semistatic test – unidirectional bearing – N = 2000 kN

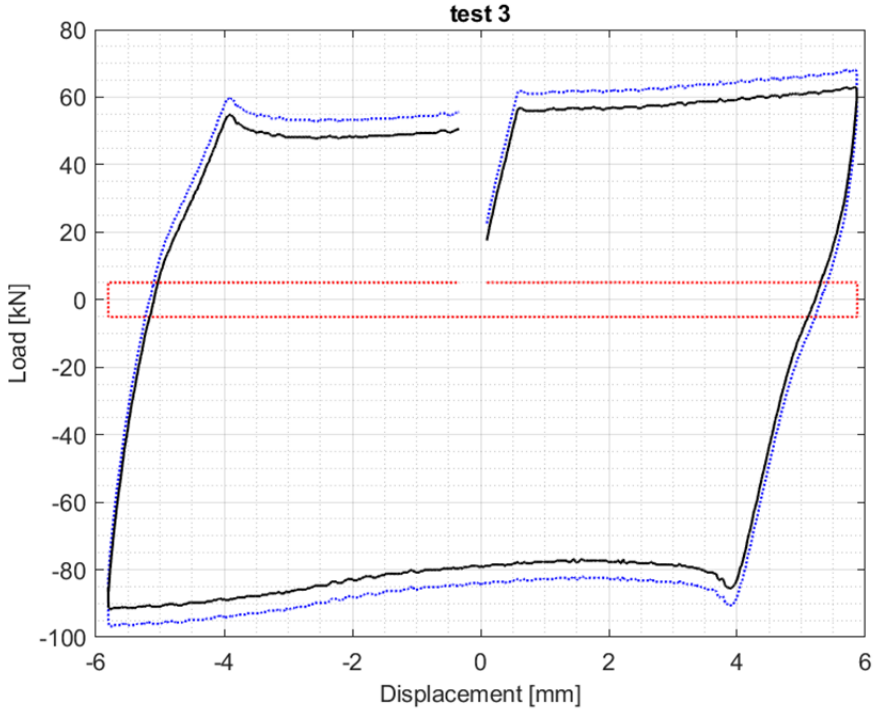

Figure 26 Semistatic test – unidirectional bearing – N = 2500 kN

A.2 Dynamic tests

Dynamic tests were carried out with imposed displacements of approximately ±45 mm at sliding velocities of 10 mm/s and 50 mm/s. The force–displacement diagrams obtained for the different vertical load levels and sliding velocities are reported in Figure 27 through Figure 38. All tests are performed without preload.

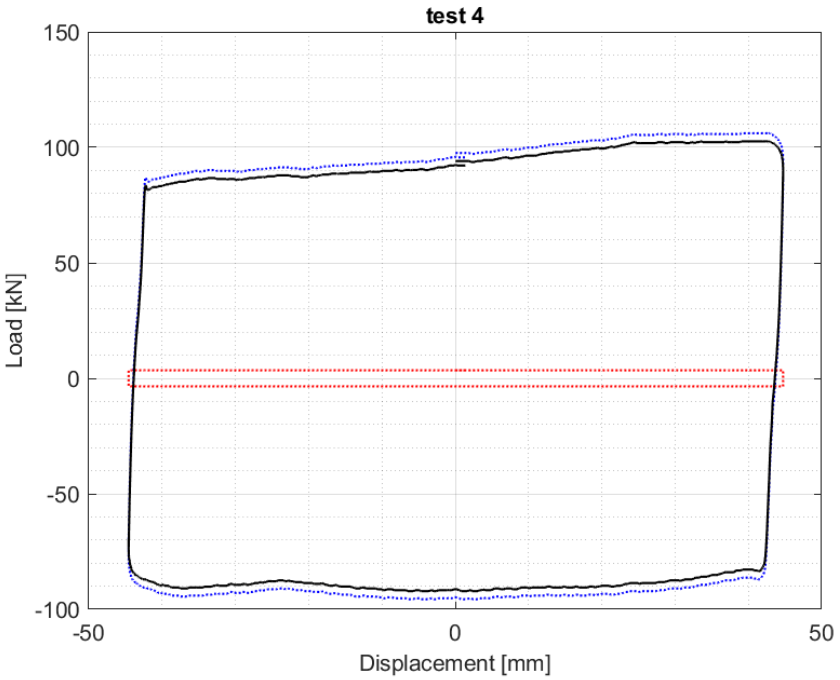

Figure 27 Dynamic test – multidirectional bearing – N = 1700 kN, v = 10 mm/s

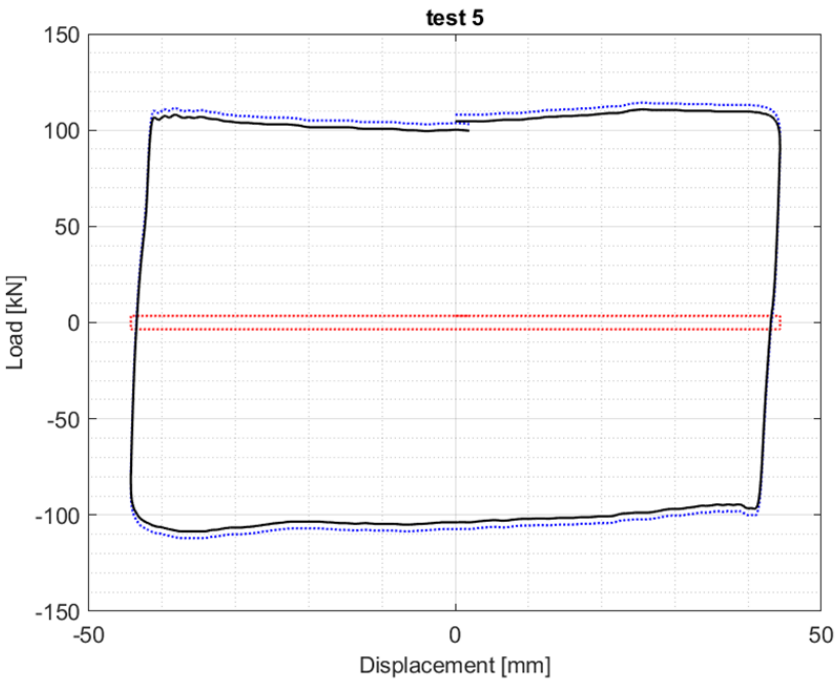

Figure 28 Dynamic test – multidirectional bearing – N = 1700 kN, v = 50 mm/s

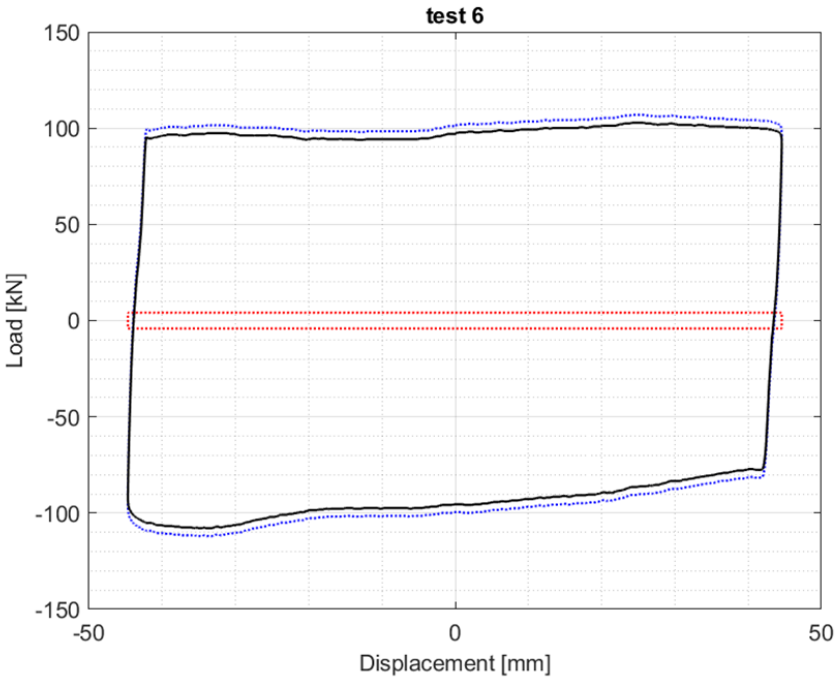

Figure 29 Dynamic test – multidirectional bearing – N = 2000 kN, v = 10 mm/s

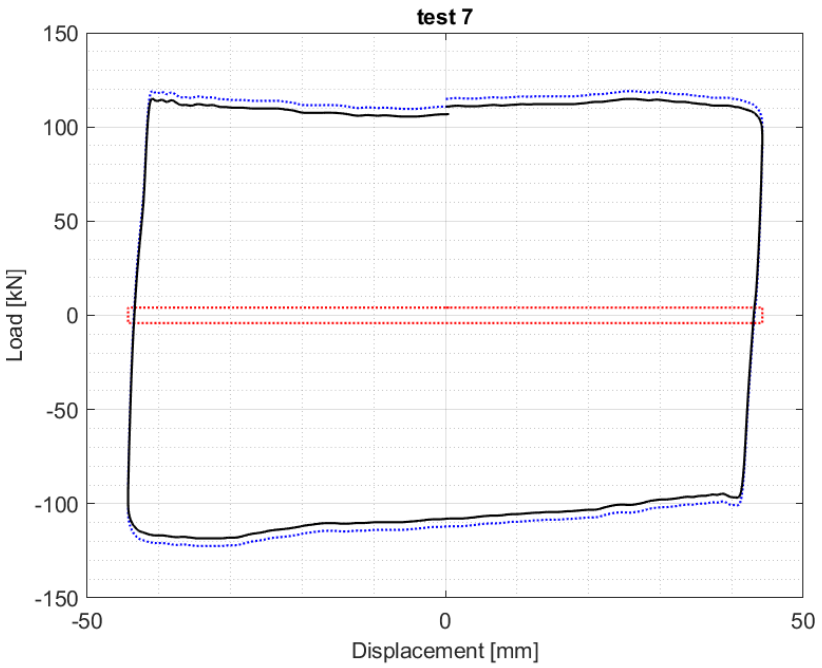

Figure 30 Dynamic test – multidirectional bearing – N = 2000 kN, v = 50 mm/s

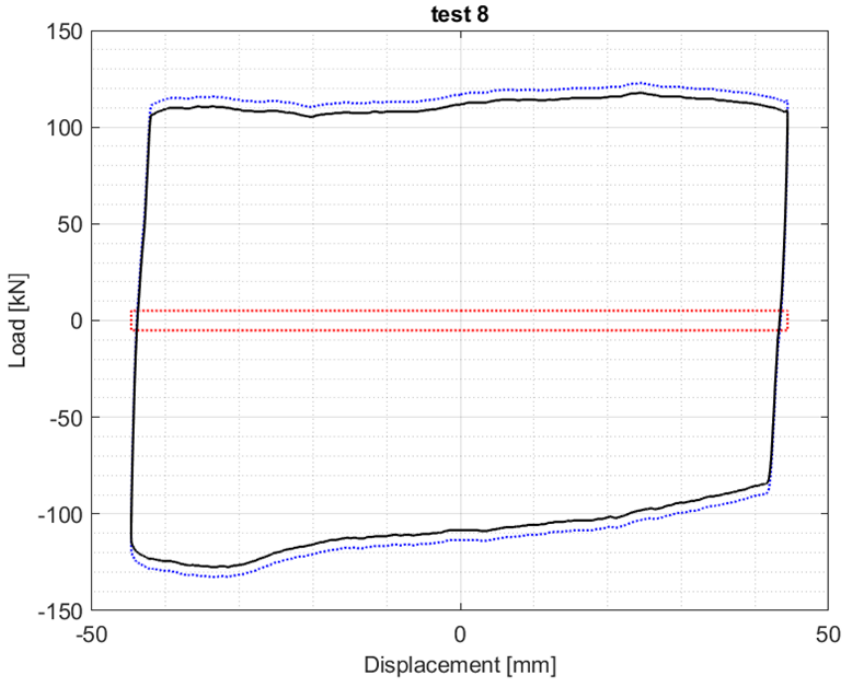

Figure 31 Dynamic test – multidirectional bearing – N = 2500 kN, v = 10 mm/s

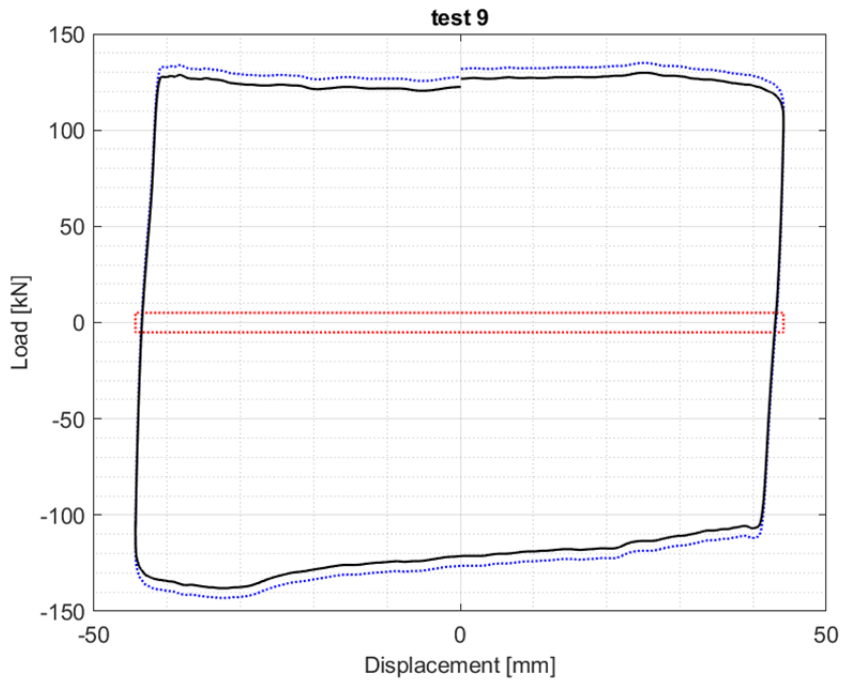

Figure 32 Dynamic test – multidirectional bearing – N = 2500 kN, v = 50 mm/s

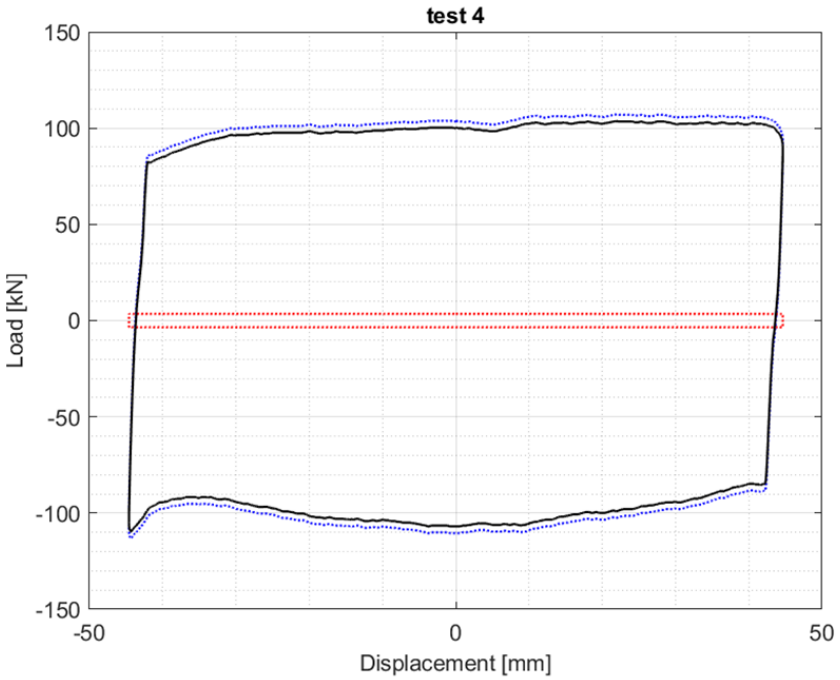

Figure 33 Dynamic test – unidirectional bearing – N = 1700 kN, v = 10 mm/s

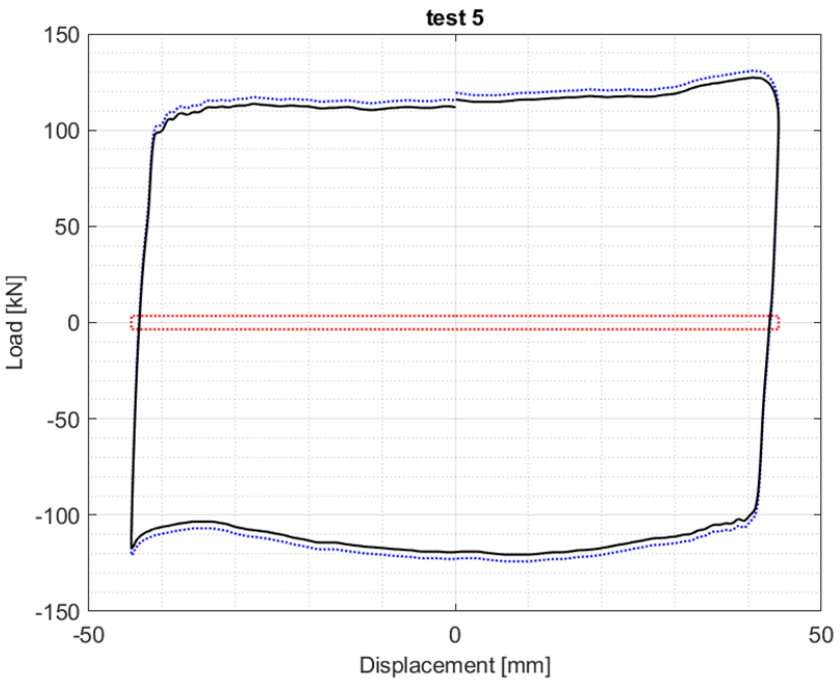

Figure 34 Dynamic test – unidirectional bearing – N = 1700 kN, v = 50 mm/s

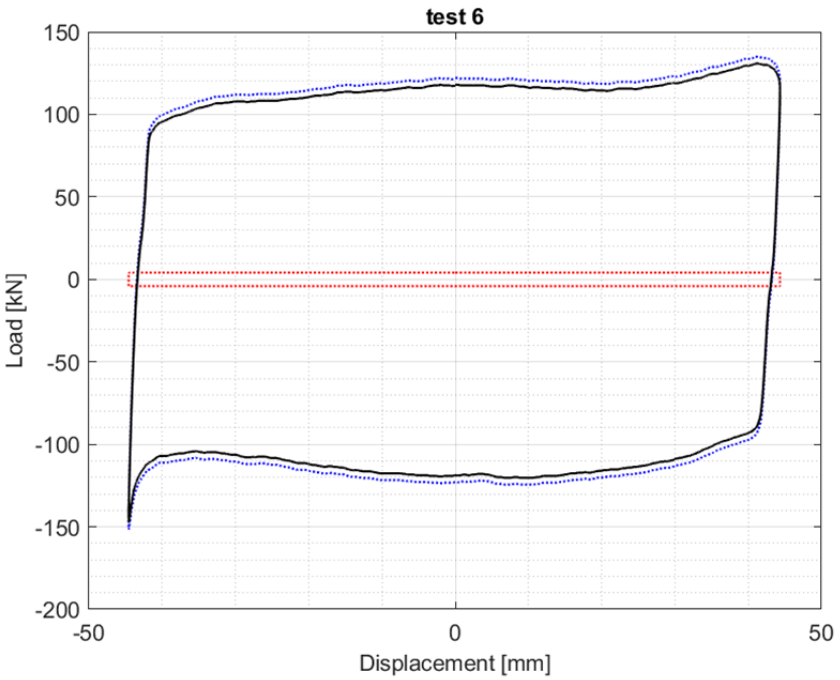

Figure 35 Dynamic test – unidirectional bearing – N = 2000 kN, v = 10 mm/s

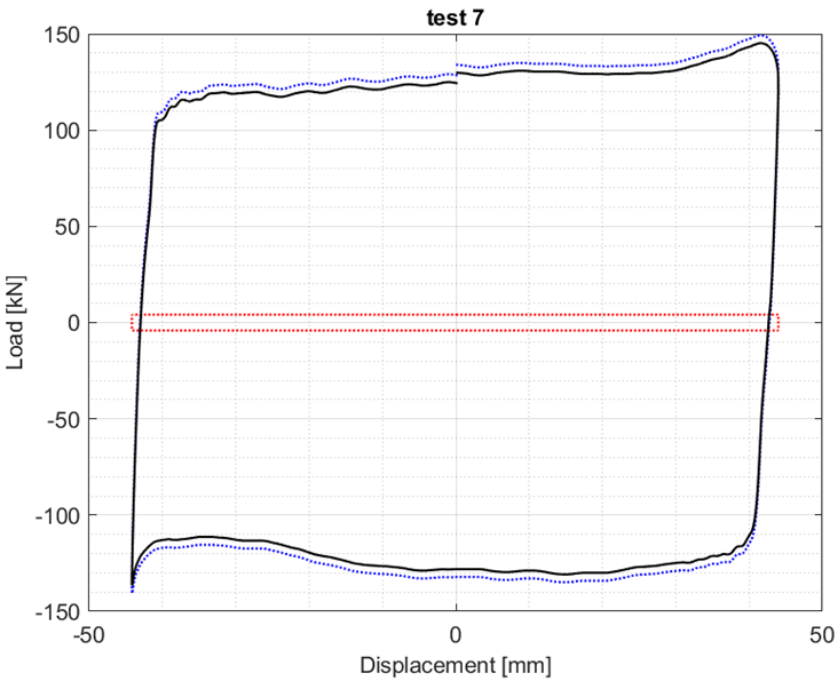

Figure 36 Dynamic test – unidirectional bearing – N = 2000 kN, v = 50 mm/s

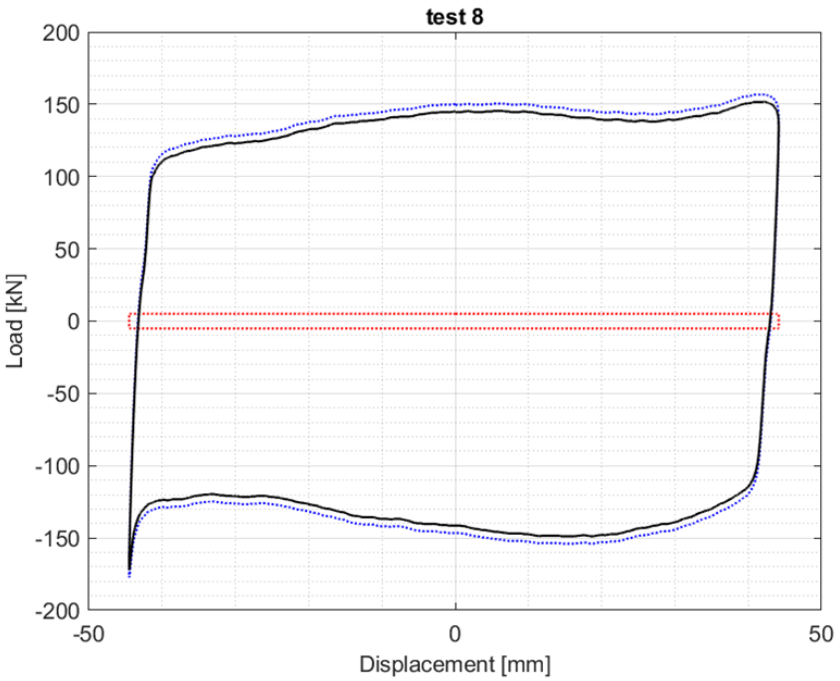

Figure 37 Dynamic test – unidirectional bearing – N = 2500 kN, v = 10 mm/s

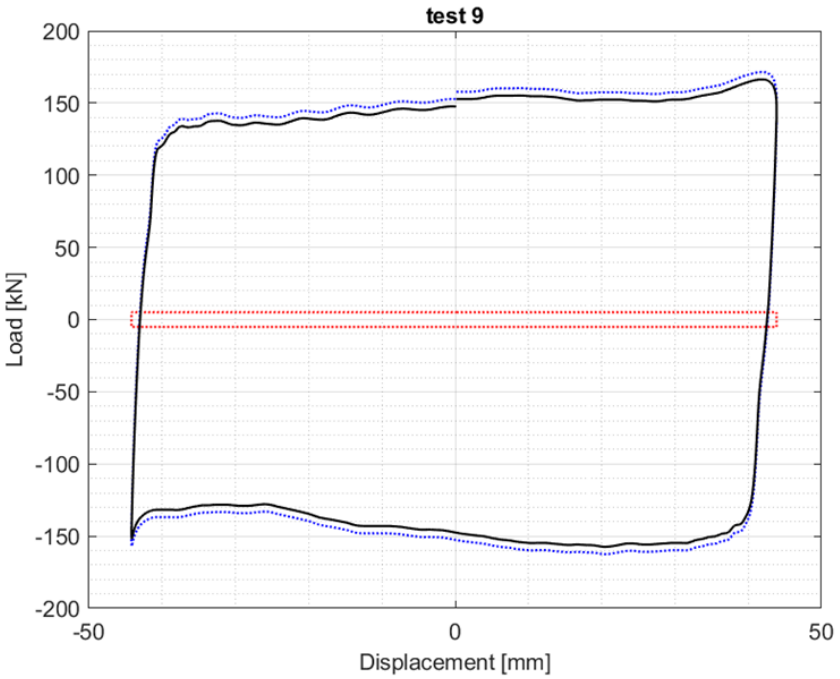

Figure 38 Dynamic test – unidirectional bearing – N = 2500 kN, v = 50 mm/s