BIAXIAL BEHAVIOUR OF RC COLUMNS BUILT WITH PLAIN REBARS

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Abstract: *A considerable number of existing reinforced concrete (RC) buildings structures were designed before 80's, when the reinforcing bars had plain surface and prior to the enforcement of the modern seismic-oriented design codes. This paper presents the results of a recent experimental campaign performed on four full-scale RC columns representative of existing structures with plain reinforcing bars. The columns were tested under constant axial load and uniaxial or biaxial lateral cyclic loading until failure. An additional column, built with deformed reinforcing bars, was also tested. All specimens have square cross-section (30x30cm) and represent a cantilever with 1.5m of span. The main experimental results are presented and discussed. The influence of bond properties on the column behaviour is evidenced by differences observed between the cyclic response of similar specimens with plain and deformed bars. The effect of the lateral loading path on RC columns built with plain bars is also presented.*

1 Introduction

Earthquakes impose multi-directional deformations on vertical structural members such as columns. Despite this, current approaches to the displacement-based assessment of existing structures adopt deformation thresholds for performance limits that are based on uniaxial cyclic tests that do not appropriately represent the range of response of columns with different detailing under earthquake loading. Observations of biaxial response of reinforced concrete columns are limited, particularly columns with plain reinforcing bars. Regarding the cyclic biaxial bending of RC columns, Bousias et al. (1995) presented an important study considering the effect of a biaxial load path with constant and variable axial load, besides other authors, namely Low & Moehle, (1987), Ludovico et al. (2013), Del Zoppo et al. (2017) and Lucchini et al. (2022) which demonstrated the relevance of considering biaxial bending on RC columns. Moreover, existing RC structures with plain reinforcing bars present a lack of ductility due to the reinforcement's poor bond-slip properties Melo et al. (2015a).

It is known that many buildings, designed according to old codes, can be more prone to serious damage under seismic action. This can be due to lower seismic design actions, use of plain reinforcing bars Melo, et al. (2015b and 2015c), poorer detailing, lap slices in critical regions, premature terminations of longitudinal reinforcement and lack of lateral confinement, which are common in existing structures built until the 80s. The cyclic loads induce progressive concrete-steel bond degradation which can lead to a significant bar slippage. Consequently, the maximum strength may not be achieved and the deformation of the elements may increase, leading the structure to partial or total collapse prematurely. Studies available in the literature, such as Melo et al. (2011) and Verderame et al. (2008) indicate that the bond-slip mechanism has a significant impact on the fixed-end rotations and may represent up to 80%~90% of the RC element overall deformability on elements built with plain reinforcing bars. The correct assessment of the behaviour of these structures is crucial to assess rigorously their safety, but also to minimize the costs associated to their retrofitting for improving the cyclic behaviour. Apart from the slippage phenomenon, old RC structures have their performance limited by other aspects such as: inadequate reinforcement detailing for seismic demands; lower concrete confinement level; lower compressive concrete strength; and designed only for gravity loads.

This paper presents the results of an experimental campaign carried out on five full-scale RC columns representative of existing structures. Four columns were built with plain reinforcing bars and one with deformed reinforcing bars. All columns don´t have any detailing for seismic loadings. Several biaxial and uniaxial lateral displacements paths and constant axial load were adopted in the tests. All the columns have the same geometry (cross-section of 30 x 30cm^2) and height of 1.5m (half column height). The obtained force-drift relationships, dissipated energy evolution and final damages are shown and compared between each other to evidence the influence of using plain reinforcing bars and biaxial cyclic loading.

2 Columns detailing, materials and test setup

2.1 Columns detailing and materials properties

Five full-scale RC columns with similar cross section and reinforcement detailing were built at the same time. The columns were designed according to the old Portuguese code REBA (1967) and without any seismic requirements. The geometry and cross-section details are presented in Figure 1. Each specimen represents a half-storey cantilever column of a 3.0m storey height, at foundation level, of a structure with three storeys. Despite the specimens have 1.65m length, the lateral loading is applied at 1.5m from the top foundation. The columns have square cross-section with dimensions of 0.30 x 0.30m^2 and a stiff block with dimensions of 0.44 x 0.44 x 0.5m^3 that simulates the foundation. The columns have 8 longitudinal reinforcing bars with diameters of 12mm (longitudinal reinforcement ratio of 1%) and stirrups of 8mm diameter spaced at 0.20m and with 90° anchorage hooks. The concrete cover is 25mm. The columns were casted together in a single phase and cured for at least 6 months.

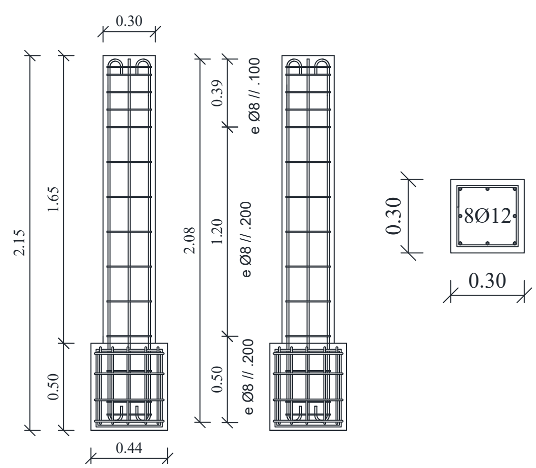


Figure 1. Geometry and reinforcement detailing (dimensions in m).

Table 1 summarises the mean values of the concrete and steel properties, where f_{cm} is the concrete compressive strength of cylinder samples (Ø150mm × 300mm) according to the standard norm NP EN 206-1 (2000), f_{ym} is the yield strength of reinforcement, f_{um} is the ultimate tensile strength of reinforcement and E is the Young's modulus.

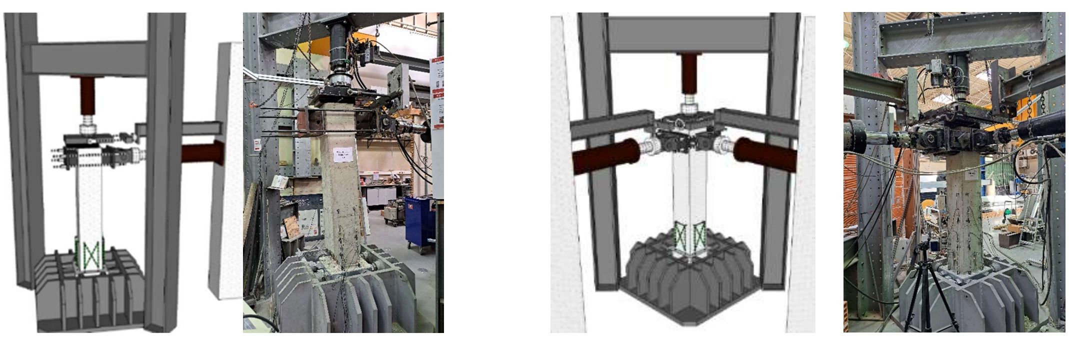
Table 1 also have information regarding the rebars surface (plain or deformed) and lateral loading adopted (uniaxial monotonic, uniaxial cyclic, biaxial circular and biaxial elliptical). The yield stress of the deformed reinforcing bars is 15% larger than the yield stress obtained for the plain reinforcing bars and the concrete is the same for all columns with a mean compressive strength of 27 MPa. The nomenclature adopted to identify the columns is: P – plain; D – deformed; UM – uniaxial monotonic; UC – uniaxial cyclic; BC – biaxial circular; and BE – biaxial elliptical.

Table 1. Mean values of the concrete and steel mechanical properties.

Column	Concrete	Steel						Bar surface	Lateral loading
		Ø8mm			Ø12mm				
	f_{cm} [MPa]	f_{ym} [MPa]	f_{um} [MPa]	E [GPa]	f_{ym} [MPa]	f_{um} [MPa]	E [GPa]		
PUM	27	410	495	198	405	470	199	Plain	Uni. mono.
PUC									Uni. cyclic
PBC									Bi. circular
PBE									Bi. elliptical
DBC		470	605	198	465	585	199	Deformed	Bi. circular

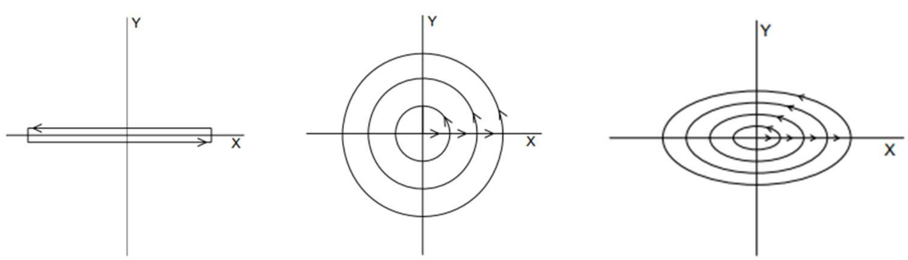
2.2 Test setup

The experimental tests were performed in a test rig available in the Structures Laboratory at Porto University developed for performing uniaxial and biaxial cyclic tests on reinforced concrete columns with constant or varying axial loads. The test rig includes a vertical actuator used to apply the axial compressive load and two horizontal actuators to apply the cyclic lateral displacements (d_c). The axial load (N) was set to a constant value of 300kN corresponding to an axial load ratio of ν=12.3%. The lateral displacements (d_c) are imposed at 1.50m from the foundation top and each demand level cycle is repeated three times, with gradually increasing demand levels. The adopted lateral load path followed the nominal peak displacement levels of 3, 5, 10, 4, 12, 15, 7, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80 (in mm) and have the shape showed in Figure 3. The displacements adopted for the semi-minor axis in the elliptical path corresponds to half value of the semi-major axis. In this test setup it is assumed that the P-Delta effects are neglected once the load is allows aligned with the column base. More information about the test setup can be found at Rodrigues et al. (2013) and Lucchini et al. (2022).



Uniaxial Biaxial

Figure 2. Test setup adopted for uniaxial and biaxial tests.



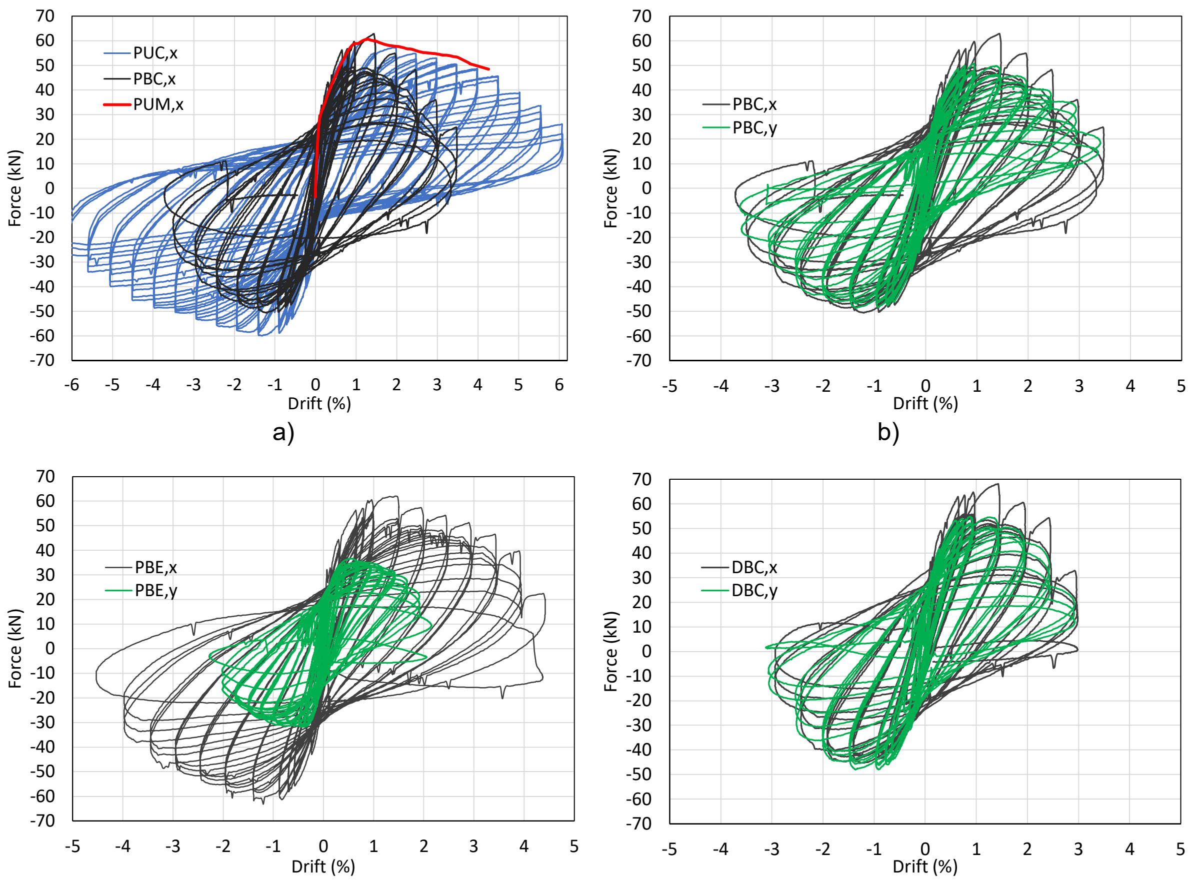
Uniaxial Biaxial circular Biaxial elliptical

Figure 3. Lateral loading path adopted on the cyclic tests.

3 Test results

3.1 Force-drift relationships

The obtained lateral force-drift relationships for all columns are shown in Figure 4. The drift values are determined dividing the imposed lateral displacement by the z position of the load point (1.5m). In the biaxial tests, when the imposed displacement goes for a new cycle amplitude, the first branch goes just in direction x such as the uniaxial test. This justifies the higher peak forces obtained in the first positive cycle for each imposed displacement amplitude. The response of column PUM is almost coincident with the column PUC envelope. Consequently, the uniaxial cyclic loading does not affect the initial stiffness and maximum capacity of RC columns with plain reinforcing bars. However, the biaxial loading has a significant influence on the cyclic response as presented in Figure 4a where it is possible observed that although the initial stiffness and peak force of columns PUC and PBC are similar, the softening and pinching effect are completely different. In columns PBC and DBC, the response is almost symmetric and equal in both directions. Column PBE has lower force in direction y because the imposed displacement is direction x is twice compared with direction y.



c) d)

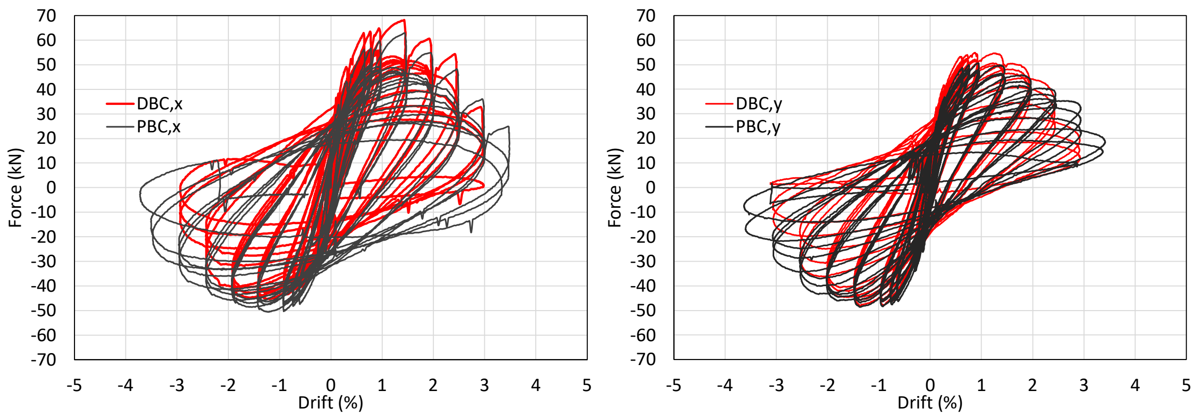
Figure 4. Force – drift relationship: a) uniaxial tests and PBC in x direction; b) column PBC in both directions; c) column PBE in both directions; and d) column DBC in both directions.

Table 2 presents the peak force (F_{max}), drift at peak force ($Drift_{Fmax}$), ultimate force (F_{ult}), drift at ultimate force ($Drift_{Fult}$) and displacement ductility at ultimate point ($\mu_{\Delta,ult}$) for all columns. The ultimate force corresponds to a drop of 20% of the peak force and the displacement ductility at ultimate point is the ratio between the displacement at ultimate point and the displacement corresponding to yield computed according to Melo, et al. (2015c). The peak force in all columns with plain reinforcing bars is almost the same and around 11% lower than the maximum strength obtained for column DBC due to the higher yield stress of the deformed reinforcement. The drift at peak force was similar in all columns, but the drift at ultimate point is much higher in the uniaxial tests than in the biaxial tests (almost double). The displacement ductility observed in column

PUM (monotonic test) is 10% and 76% larger than in columns PUC e PBC, respectively. The ductility obtained for column DBC with deformed reinforcing bars is 20% larger than column PBC with plain reinforcing bars. Therefore, the weak bond properties of the plain reinforcing bars reduce the ductility capacity of the RC columns.

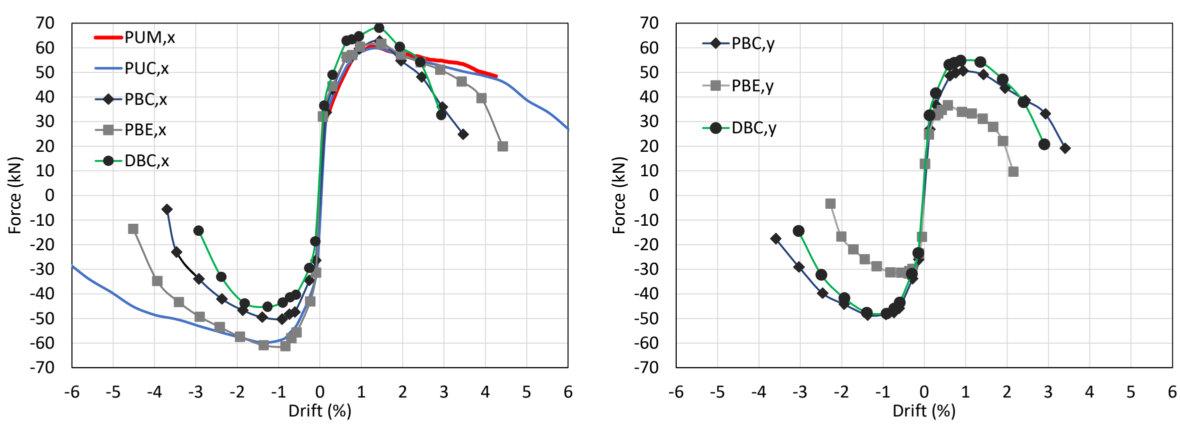
Table 2. Peak force, drift at peak force, ultimate force, drift at ultimate force and displacement ductility.

Column	Direction	F_{max} [kN]	$Drift_{Fmax}$ [%]	F_{ult} [kN]	$Drift_{Fult}$ [%]	$\mu_{\Delta,ult}$
PUM	x	60.6	1.3	48.5	4.3	8.8
PUC	x	60.0	1.4	48.0	4.1	8.0
PBC	x	62.8	1.4	50.2	2.3	5.0
	y	50.7	0.9	40.6	2.3	
PBE	x	61.7	1.5	49.4	3.1	4.8
	y	36.6	0.6	29.3	1.6	
DBC	x	68.1	1.4	54.5	2.4	6.0
	y	54.8	0.9	43.8	2.1	



a) b)

Figure 5. Force – drift relationship for columns PBC and DBC: a) direction x; and b) direction y.



a) b)

Figure 6. Force – drift envelopes: a) direction x; and b) direction y.

Figure 5 shows the force-drift relationship for column PBC and DBC in each direction for direct comparison. The cyclic results are not significantly different between each column, namely in terms of initial stiffness, peak force and softening. However, column DBC presents lower pinching effect than column PBC. Therefore, the global response of the column PBC with plain reinforcing bars has similar cyclic response compared with column DBC. In both columns the response is not perfectly symmetric once for positive imposed displacements, the lateral force is slightly larger than for negative displacements since the top column goes first for positive direction where accumulate damages that affect the response in the negative direction.

The envelopes of the force-drift relationship are shown in Figure 6. The envelopes follow a similar tend until the peak load and then the softening is more evident in the biaxial tests than in the uniaxial ones. The peak force in direction y on column PBE is lower than in direction x once when it is reached the peak force in direction y (around 1% drift) there are already damages due to the drift imposed in direction x that is twice the value of direction y.

3.2 Dissipated energy evolutions

The accumulative hysteretic dissipated energy evolution for each column is presented in Figure 7. The ultimate points for each column are also identified as circular black marks. The dissipated energy for the biaxial tests is computed as the sum of the accumulative dissipated energy in direction x and y. Until the ultimate point, columns PUC, PBE and DBC dissipated 107%, 53% and 27% more than column PBC, respectively. The results show that column PUC, tested under uniaxial loading, dissipated double energy compared to the similar column PBC tested under biaxial loading, demonstrating the large influence of the lateral load conditions on the energy dissipation capacity, once the ultimate drift is higher in the uniaxial test. But for the same level of drift, PUC dissipates less energy than the other columns. It is also shown that RC columns with plain reinforcing bars dissipate less energy than similar columns with deformed reinforcing bars under the same loading conditions. Moreover, for the same level of drift, column DBC is the one that dissipates more energy due to the better bond properties. Column PBE dissipates more energy than PBC because the ultimate drift is larger on PBE.

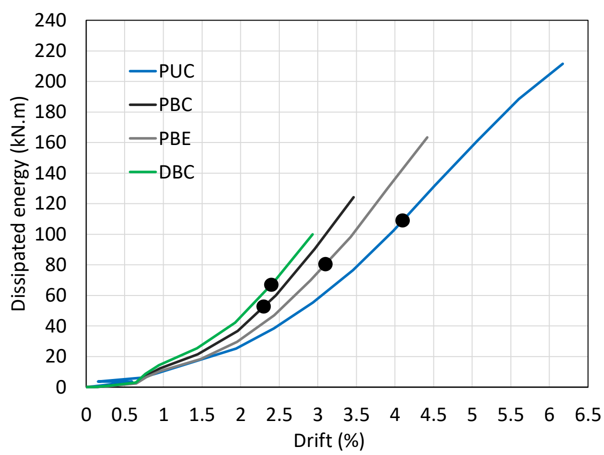


Figure 7. Hysteretic dissipated energy evolutions.

3.3 Damages at the end of the test

The final damages observed at the end of the test are presented in Figure 8. Column PUM only presents two big horizontal cracks in the face that is in tension at the base of the column and concrete cover spalling in the compression face close to the foundation. On the other hand, the columns cyclic tested show horizontal cracks, concrete cover spalling and buckling of the longitudinal bars. Only in column PUC two longitudinal bars broken. The observed plastic hinge (here assumed as the length where concrete cover spalling was observed) on columns PUM, PBC, PBE and DBC were 17cm, 25cm, 25cm and 37cm, respectively. The plastic hinge length of the columns tested under biaxial loading presented larger values than column PUM. The plastic hinge of column DBC is 48% higher than column PBC demonstrating that RC elements with deformed reinforcing bars can better spread the damages along the column hight. The depth of the concrete spalling on the biaxial tests is around twice the dept observed on the uniaxial cyclic test. The biaxial loading accelerate the damages and they are more severe than in the column tested under uniaxial cyclic loading. All the columns fail in bending due to the orientation of the cracks and no stirrups rupture was observed.

Figure 8. Final damage observed at the end of the tests.

4 Conclusions

Five RC columns were tested under monotonic or cyclic lateral loading and constant axial load until reach the collapse. Uniaxial and biaxial lateral loading were adopted on the cyclic tests, plain reinforcing bars were used to build four columns and one similar column was built with deformed bars to demonstrate the influence of using plain reinforcing bars on the seismic performance of RC columns. Based on the test results the following conclusions can be draw:

- The maximum strength is not significantly affected by the lateral loading type. However, the ultimate drift and ductility obtained on the cyclic tests are substantially lower than on the uniaxial tests. Therefore, biaxial loading accelerates the strength degradation and softening.
- The column with deformed reinforcing bars, DBC, dissipated 27% more dissipated energy than the corresponding column with plain reinforcing bars, PBC, that demonstrate the lower dissipation energy capacity of RC columns with plain reinforcing bars.
- The plastic hinge observed on column PBC was 48% lower than on column DBC indicating that the damages on RC columns with plain reinforcing bars are more concentrated.
- The damages observed on columns tested under biaxial loading occurred for lower drift levels and the concrete spalling was deeper than observed in the uniaxial test.
- The shape of the biaxial loading influences the capacity of RC columns once for column PBE, tested under elliptical loading, the peak force obtained in direction y was around 60% of the peak force in direction x.

5 Acknowledgements

This work is financially supported by national funds through the FCT/MCTES (PIDDAC), under the project 2022.05721.PTDC and by Base Funding - UIDB/04708/2020 and Programmatic Funding - UIDP/04708/2020 of the CONSTRUCT - Instituto de I&D em Estruturas e Construções - funded by national funds through the FCT/MCTES (PIDDAC).

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