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# Development and Validation of an Experimental Setup for Biaxial Cyclic Testing of Steel Tubular Columns

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**Abstract**

This study presents the preparation and validation of an experimental campaign aimed at investigating the behaviour of steel tubular columns under biaxial cyclic loading. It describes the selection of specimens, the design of test setup, and the numerical simulations performed to verify the effectiveness of the proposed support system. The results confirm the setup's ability to replicate fixed-end boundary conditions while minimizing unwanted load effects.

## 1 INTRODUCTION

In recent decades, significant progress has been made in understanding and predicting the structural collapse of steel structures subjected to earthquake-induced loading. [1]. When earthquakes occur, the seismic forces act on buildings in multiple directions simultaneously, presenting evident challenges for accurate prediction of response. In order to realistically estimate a building's behaviour, factors such as its orientation relative to the seismic forces and structural irregularities must be considered. This leads to the growing use of three-dimensional models. While the response characteristics of steel elements subjected to monotonic and unidirectional cyclic lateral loading are well-established, it is still essential to investigate the behaviour of structural components subjected to biaxial cyclic bending [2].

Concurrently, the utilization of tubular members is gaining popularity and offers several advantages, primarily due to the torsional stiffness resulting from their closed shape and the high moments of inertia available in orthogonal directions, reducing the need for lateral bracing compared to open sections [3]. However, the existing body of literature investigating the performance of steel elements subjected to bidirectional cyclic lateral loading is relatively limited [4]

Experimental testing stands out as the most precise method for characterizing the behaviour of steel members and is therefore regarded as the benchmark for validating numerical models. Despite its undeniable accuracy, the utilization of experimental testing predominantly finds its application in research settings due to the rigorous demands on specialized facilities, equipment, personnel, and the substantial allocation of resources, including materials, consumables, time, and associated costs [5]

The work presented in this study aims to describe the preparation process of an experimental campaign currently underway, from the selection of specimens to be tested to the performance of numerical analyses in finite elements, seeking to predict possible obstacles and necessary adaptations in the setup and in the laboratory where the tests will be carried out.

## 2 EXPERIMENTAL CAMPAIGN

### *2.1 Specimens*

The experimental campaign aims to evaluate the structural behaviour of steel tubular section columns. A total of 3 circular hollow sections, 4 square hollow sections and 1 rectangular hollow section were selected (Table 1). The free length of each specimen was set to 1.5 m. The axial load level, n, is defined as the ratio between the axial load applied to the specimen and the axial resistance of the cross-section, which is estimated based on the available properties of the steel. Two levels of axial load were targeted in the test campaign, namely n = 20% and n = 0%.

Table 1: Investigated geometrical parameters.

| Specimen | b/t (MPa) | Class (EC3) |
|---|---|---|
| C219x10-0 | 21.9 | 1 |
| C219x10-20 | 21.9 | 1 |
| C219x6-0 | 36.5 | 2 |

| | | |
|---|---|---|
| C219x6-20 | 36.5 | 2 |
| C219x4-0 | 54.8 | 3 |
| C219x4-20 | 54.8 | 3 |
| S220x10-0 | 22.0 | 1 |
| S220x10-20 | 22.0 | 1 |
| S220x8-0 | 27.5 | 1 |
| S220x8-20 | 27.5 | 1 |
| S220x6-0 | 36.7 | 1 |
| S220x6-20 | 36.7 | 1 |
| S220x5-0 | 44.0 | 1 |
| S220x5-20 | 44.0 | 2 |
| R200x100x10-0 | 20.0 | 1 |
| R200x100x10-20 | 20.0 | 1 |

### *2.2 Loading Paths and Protocol*

The specimens will be subjected to lateral loading under a displacement-controlled regime, with increasing amplitudes, following a load protocol based on the symmetric cyclic loading protocol provided in ANSI/AISC 341-16 [6] presented in Figure 1. The schematic representation of the load paths is also illustrated in Figure 1. In the unidirectional 0º path, the specimens are solely subjected to deformation along the x-direction. In the unidirectional 90º path, the specimens are exclusively deformed along the y-direction. In the case of bidirectional loading, the paths consist of displacement cycles with square, circular, and rhombus shapes in the lateral displacement space. Although bidirectional loading paths are commonly used in literature, they may not fully capture the complexity of real seismic loading scenarios. Further research is needed to develop loading protocols that more accurately reflect the dynamic nature of seismic events.

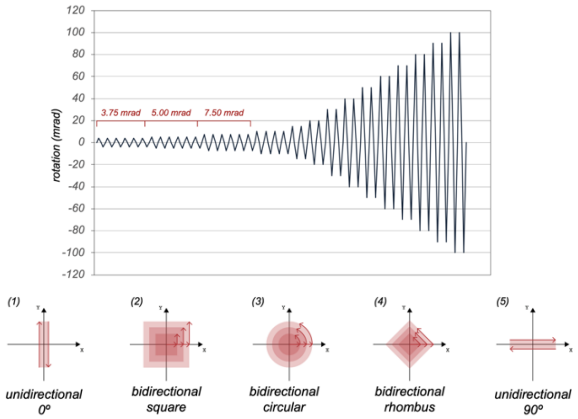



Figure 1: Loading protocol and paths

## 3 TEST SETUP

Figure 2 shows the setup to be used for the experimental campaign. The system consists of two horizontal actuators, each with a 500kN capacity and a stroke of +/-150mm, to apply the lateral loads, and a vertical actuator with a 700kN capacity to apply the axial load. Two steel reaction frames and one lateral reaction wall will be employed to support the setup. The specimens and reaction frames must be anchored to the laboratory's slab using prestressed steel bars to prevent sliding or overturning during testing.

As previously mentioned, a constant axial load will be applied to the columns while the lateral load is cycled under displacement-controlled conditions. Since the axial load actuator remains stationary while the column specimen deflects laterally during the test, a special device, consisting of two sliding steel plates, is placed between the top section of the column and the actuator to minimize any unintended friction forces.

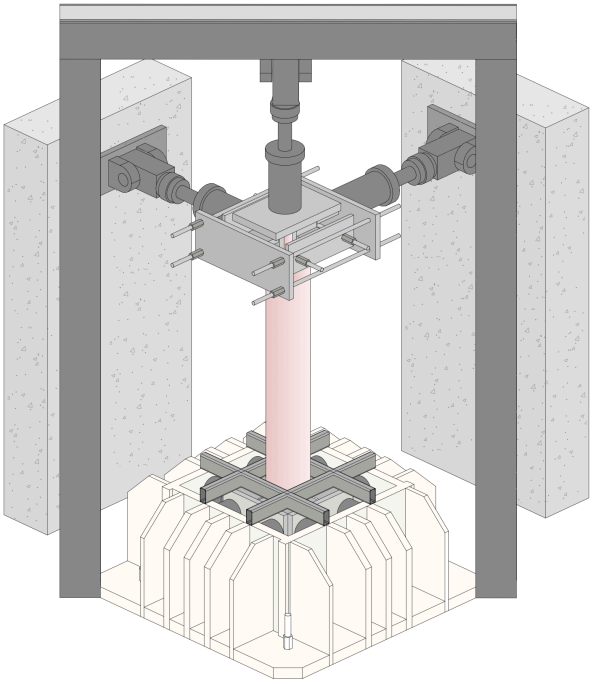


Figure 2: Experimental setup

Since the test simulates the behaviour of a cantilever column, the base of the member must be fully fixed. To achieve this, a steel box testing device available at the Laboratory of Earthquake and Structural Engineering (LESE) at the Faculty of Engineering, University of Porto (FEUP), will be used [7]. Due to the characteristics of the steel box testing device (500mm height) and the specimen free length of approximately 1500 mm, the columns should have a total length of 2000 mm. Testing will be conducted either up to specimen failure or until reaching the range limits of the actuator.

### *3.1 Testing device*

The testing device features a steel base plate measuring 1400 x 1400 x 60 mm, which is securely anchored to the slab using four Ø25 mm rods inserted into holes located near the corners. The setup includes four steel lateral plates, each measuring 500 mm high and 50 mm thick, welded together and to the base plate. To enhance the rigidity of the connection to the base plate, five stiffeners are welded to the exterior of each lateral plate. This design

results in internal dimensions of the steel box measuring 750 x 750 mm.

Inside the box, compact hydraulic cylinders are installed, with four sets per plate. Each cylinder has 60 mm of stroke and a force pressure of 45 t. Each lateral plate of the box has hydraulic cylinders connected by rigid tubes, which carry high-pressure fluid from the Hydraulic Power Unit (HPU) to the cylinders. A valve is installed for each cylinder - effectively five per lateral plate: one for each cylinder and one for the system in the lateral plate - allowing the operator to selectively activate only the desired actuators.

To ensure proper basal restraint and effective load transfer, additional filling steel parts should be positioned between the cylinders and the specimen, as illustrated in Figure 3. Three sets of steel parts were designed to envelop the lower parts of the profiles to be tested (one for each selected cross-section: circular, square and rectangular). Since the external dimensions of the sections are repeated (changing only the thickness), it is possible to use each set for all profiles with the same geometry. In addition, four steel plates will be positioned between the parts and the cylinders. It is important to highlight that the parts were designed considering a small gap between them and the member, to ensure that, upon the activation of the cylinders, the parts touch the column first. This prevents the components from merely being tightened against each other, which would leave the profile loose.

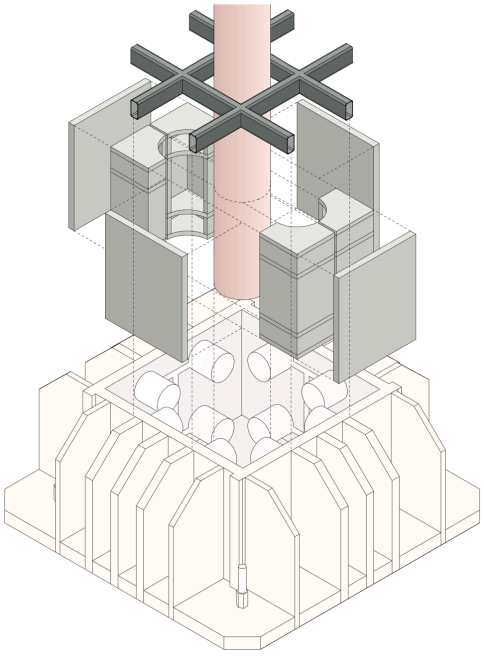


Figure 3: Schematic view of the setup assembly

In addition to the use of steel parts and plates to fill the internal part of the box, as previously mentioned and illustrated, it is proposed to fill the lower part of the tubular section, located inside the box, with concrete. The objective is that the concrete prevents the profile from deforming due to the tightening and friction between the cylinders (and filling plates) and the walls of the columns.

The Hydraulic Power Unit (HPU) in the laboratory operates at 700 bar, providing enhanced safety during the use of hydraulic cylinders. These cylinders must not be subjected to any vertical loads on their pistons. To prevent the generation of vertical lateral forces, a metal grid has been proposed to be placed above the test specimens and bolted to the test box. This grid must be sufficiently rigid to avoid deformation, which could otherwise introduce friction forces. Additionally, to further minimize friction, a Teflon sheet is proposed to be placed between the cylinder faces and the metal plates in contact with them.

## 4 NUMERICAL VALIDATION

To evaluate the efficiency of the proposed solution to simulate the fixed support conditions of the members to be tested, numerical analyses were carried out to validate the suggested strategies, i.e. the filling with concrete, the use of metal parts and plates that restrict and conduct the applied loads and the grid. A hollow circular column inserted in the setup was numerically modelled under biaxial monotonic loading. Subsequently, the results obtained were compared with those obtained in idealized/theoretical conditions - completely fixed base in all directions.

### *4.1 FE Model*

The model, developed in ABAQUS software [8], consists of a steel hollow tubular member with a circular cross-section (as mentioned before, the free length is 1500 mm, but an additional 500 mm of length inside the box must be considered). The member plates were modelled using quadratic shell elements (S4R), known to accurately capture the post-buckling behaviour. To ensure accuracy and simulate any lateral and torsional buckling, a very fine mesh size of b/20 with uniform density along the entire length of the members was used. At the base of the steel profile, a 500 mm long concrete filling was modelled with solid elements of type C3D20R. At this same height, a partition was created in the steel member, dividing it into 2 parts (one measuring 500 mm and the other 1500 mm – the free length). The steel material properties described in Table 2 were used - a combined isotropic–kinematic hardening law with no strain rate effects is considered [9], with Poisson's coefficient equal to 0.3 and Young's Modulus (E) equal to 210 GPa. - and the concrete was modelled assuming linear elastic behaviour, with Poisson's coefficient equal to 0.2 and Young's Modulus (E) equal to 30 GPa.

Table 2: Nonlinear isotropic and kinematic hardening parameters

| Material | $\sigma 0$ (MPa) | $C_1$ (MPa) | $\gamma 1$ | $C_2$ (MPa) | $\gamma 2$ |
|---|---|---|---|---|---|
| S355 | 402.9 | 180605 | 930.3 | 6.4 | 499.3 |

The steel parts, plates and the grid shown in Figure 3 were modelled considering the same material parameters used for the hollow tubes, as presented in Table 2. "Surface-to-surface" interactions were created between the steel parts, plates, grid and the member. The interfaces were characterized by specifying “hard contact” in the normal direction, which permits the separation of the interface under tensile conditions while prohibiting penetration during compressive conditions. A friction coefficient of 0.3 was utilized [10]. At the external faces of the places, other steel plates were modelled to simulate the box and the actuators, and theses external plates had their displacements and rotations prevented in all directions. The top of the column was excited under a monotonic biaxial loading, with a 30º angle in relation to the x-direction, forming a diagonal with components in both x and y directions

For the theoretical model, at the base of the member the translations about x, y and z-directions as well as the rotation about the z-axis are restrained at one end. At this same end, a flexural spring is introduced to restrain rotations about the x- and y-axes and simulating the deformability of the test setup. In this model, the experimental setup was not modelled, and the same load path was applied.

. The results obtained with the numerical model of the setup were compared with those obtained in idealized/theoretical conditions (Figure 4) and show that a good correlation was achieved between the two models analysed for this study (theoretical and simulating the experimental setup, respectively), indicating a strong correlation between the results. Furthermore, the vertical loads computed in the external plates were very low and the deformation of the grid was very small (around 0.5mm in the worst situation), confirming the applicability of the setup developed for the experimental tests.

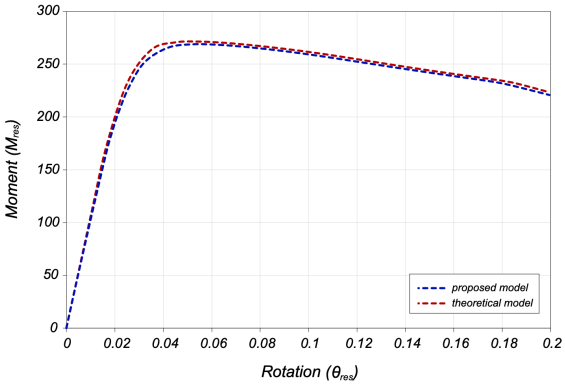



Figure 4: Monotonic curves obtained for the proposed setup (blue line) and the theoretical model (red line) under biaxial bending.

## 5 CONCLUSIONS

The proposed experimental setup was numerically validated and demonstrated to effectively replicate the idealized fixed-end boundary conditions. The system proved capable of ensuring proper load transfer and restraining undesired displacements and rotations, making it suitable for testing tubular steel columns under biaxial cyclic loading.

## ACKNOWLEDGEMENTS

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