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SEISMIC NUMERICAL MODELLING OF ELECTRICAL CABINETS

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Abstract

The seismic performance of non-structural elements, such as electrical cabinets, has been proven to be of crucial importance when assessing the global performance of modern code-compliant facilities. The seismic performance of several typologies of electrical cabinets was recently assessed in a shake table testing campaign conducted in the 6DLAB laboratory of the Eucentre Foundation, located in Pavia, Italy. Using the experimental data obtained from the testing campaign, numerical models were calibrated to reproduce the hysteretic response of the electrical cabinets. Three different criteria were considered for the calibration of the numerical models: i) absorbed energy time-history, ii) relative displacement time-history, and iii) force-relative displacement hysteretic response. The developed numerical models can approximate the seismic response of the electrical cabinets when subjected to the seismic testing protocols of increasing intensity used during the testing campaign. Furthermore, the developed numerical models are useful to generalize the experimental results obtained in the testing campaign and can be used to conduct additional numerical studies on the seismic performance of other configurations of electrical cabinet systems.

Keywords: Non-structural elements, electrical cabinets, hysteretic response, numerical modelling, absorbed energy.

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1 INTRODUCTION

Non-structural elements (NSEs) became a crucial aspect of earthquake engineering after the introduction of performance-based seismic design by the Pacific Earthquake Engineering Research Center in the early 2000's [1]. The necessity of improving the global seismic performance of code-compliant facilities shed some light into previously overlooked issues, as for example the higher vulnerability exhibited by NSEs in comparison to their structural counterpart, especially at lower seismic intensities [2,3].

In order to improve the seismic performance of NSEs, such as electrical cabinets, several experimental and numerical studies have been conducted during the last two decades by the earthquake engineering community. As part of these efforts, a shake table experimental campaign was conducted recently to assess the seismic performance of several typologies of electrical cabinets in the 6DLAB laboratory of the Eucentre Foundation, located in Pavia, Italy [4]. During this experimental campaign, seven different specimens of electrical cabinets were tested using two different loading protocols, namely the Telcordia-GR-63-CORE loading [5] and the protocol developed recently as part of a proposed seismic classification procedure for NSEs in Italy [4, 6]. The installed instrumentation consisted of an array of accelerometers to measure the acceleration response of the specimens, and horizontal and vertical potentiometers to measure the horizontal displacement and uplift of the specimens, respectively. Details on the experimental campaign can be found in Merino et al. [4].

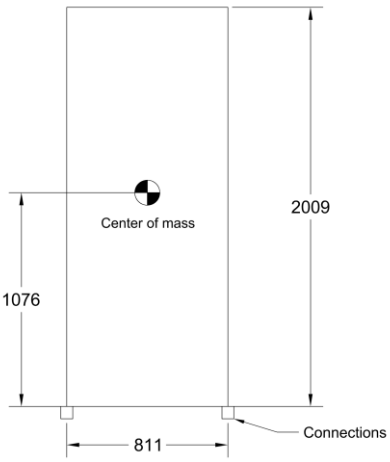
While comprehensive testing is a necessary process to characterize the seismic response of non-structural systems, due to economic and functional limitations it is usually not possible to test every possible geometrical and material configuration of a given non-structural system typology. Therefore, the calibration of numerical models based on experimental data is often conducted to generalize the results obtained from experimental campaigns to be used in different geometrical and material configurations than the ones tested. It should be noted that when using numerical models calibrated based on experimental results, attention should be paid to the characteristics of the specimen (i.e., geometry, type of profiles, connections between the load bearing elements, etc.), given that different constructive solutions could lead to NSEs apparently similar but characterized by different seismic responses. Analogously to the case of structural systems, the detailing adopted for the seismic design of a NSE can play a critical role, deeply influencing the ductility and energy dissipation capacity.

In order to generalize the results obtained from the experimental campaign conducted by Merino et al. [4], this paper develops numerical models based on one of the tested cabinet specimens. The developed numerical models were calibrated based on the relative displacement time-history, absorbed energy time-history, and force-relative displacement hysteretic response. The objective was to generate calibrated models that are able to approximate the response of the electrical cabinets when subjected to the loading protocols used in the experimental campaign and that can be used to conduct additional numerical studies on the seismic performance of other configurations of electrical cabinets.

2 TEST SPECIMEN SELECTED FOR THE CALIBRATION

The seven electrical cabinets specimens tested during the experimental campaign were divided in two groups. Group 1 consisted of four different electrical cabinet specimens mounted on the surface of the shake table and tested at the same time. On the other hand, Group 2 consisted of three electrical cabinet specimens, one mounted on a rigid steel frame rigidly attached to the surface of the shaking table to simulate a wall-mounted cabinet, while the other two specimens were mounted on the surface of the shake table, as the specimens of Group 1. The

Specimen 4 of Group 1 was selected to conduct the calibration of the numerical models, given that during the shake table tests this specimen experienced progressive damage as the intensity of the loading protocols increased, therefore allowing for a proper calibration of the response along the complete range of elastic and inelastic response. Figure 1 shows a photograph and the geometry of the selected specimen for the calibration of the numerical models.



a) b)

Figure 1. Specimen selected for the calibration of the numerical models: a) Photograph of the specimen, and b) its respective geometry along the shorter direction (x direction). Units in millimeters.

3 NUMERICAL MODELS

Two different modelling approaches were followed to recreate numerically the response of the electrical cabinets documented during the experimental campaign: i) a single-degree-of-freedom (SDOF) system calibrated to match the relative displacement time-history, absorbed energy time-history, and force-relative displacement hysteretic response obtained during the experimental campaign, and ii) a mechanics-based multiple-degree-of-freedom (MDOF) system in which the calibration of the response of the specimen attachments and the specimen internal support structure were conducted separately, based on proper decomposition of the recorded experimental response. The separately calibrated degrees of freedom of the MDOF were then combined to recreate the relative displacement time-history, absorbed energy time-history, and force-relative displacement hysteretic response observed during the experimental tests. In the following sections, each of the modelling approaches is described in detail. The absorbed energy was defined as the integration over time of the force experienced by the specimen integrated through its displacement.

3.1 Single-degree-of-freedom model

The first numerical model, calibrated with the experimental shake-table test data consisted in a SDOF damped system with a non-linear spring (K_c), and a dashpot (C) supplying additional energy dissipation beyond the hysteretic energy dissipated by the yielding of the non-linear spring. Figure 2 shows a schematic view of the proposed SDOF modelling approach. The calibration of the model was conducted by using the open-source platform OpenSees [7]. The *Hysteretic* tri-linear material from the OpenSees material library [9] was used to calibrate the non-linear spring K_c (Figure 2). A damping ratio equal to 4.5% was considered for the definition of the dashpot element in order to improve the match of the absorbed energy time history.

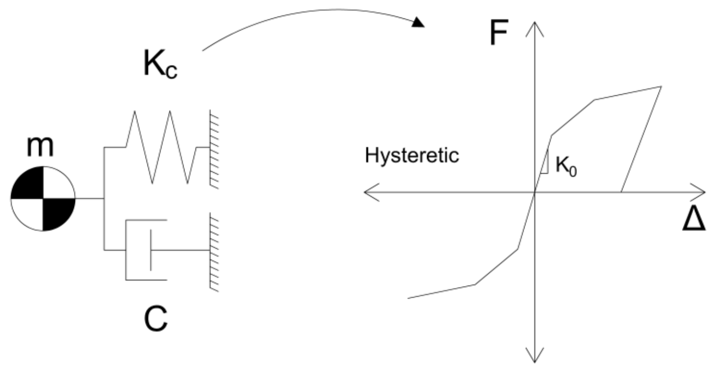


Figure 2. Modelling approach selected for the SDOF numerical model of the electrical cabinets.

3.2 Multiple-degree-of-freedom model

The second model consisted in a mechanics-based MDOF model, which has a pair of non-linear springs to capture the response of the base connections of the electrical cabinet specimens, and another non-linear spring to capture the lateral response of the internal support structure of the electrical cabinet. For the calibration of this model, the response of the base connections and the internal support structure of the electrical cabinet specimen were decoupled and calibrated independently. Figure 3 shows a schematic view of the modelling and calibration approach considered for the MDOF model of the electrical cabinets. The developed MDOF model was inspired by the model proposed by Feinstein and Moehle [8]. Note that no additional damping was applied to this model beyond the hysteretic damping provided by the yielding of the non-linear springs. As for the case of the SDOF model, the open-source platform OpenSees was used for the calibration of the numerical model. A *Hysteretic* tri-linear material was used for the calibration of the base non-linear springs (K_a) that are meant to simulate the response of the electrical cabinet attachments to the ground slab, while a *SelfCentering* (flag-shaped) material was selected to calibrate the non-linear spring meant to simulate the response of the internal support structure of the electrical cabinet (K_c) [9]. The calibration of K_a and K_c was conducted by decoupling the numerical modelling, as shown in Figure 3a and Figure 3b. The force-relative displacement hysteretic response, absorbed energy time-history, and the relative displacement time-history of the specimen obtained at the lower intensity range of the experimental campaign were used for the calibration of the K_c non-linear spring, given that, at the lower intensity range, the response of the electrical cabinets was strongly dominated by the response of the internal support structure, with no rocking of the specimen occurring. On the other hand, the non-linear springs K_a were calibrated by using the response of the specimen at the higher intensity range, where the response of the specimen was mainly driven by the non-linear response of the base attachments, with significant rocking of the specimen being mobilized. The calibration process was completed by integrating the independently calibrated non-linear springs K_a and K_c in a single numerical model, as shown in Figure 3c, and adjusting the calibrated parameters of the non-linear spring K_a in order to match the response of the numerical model to that of the specimen across the complete intensity range of the experimental campaign.

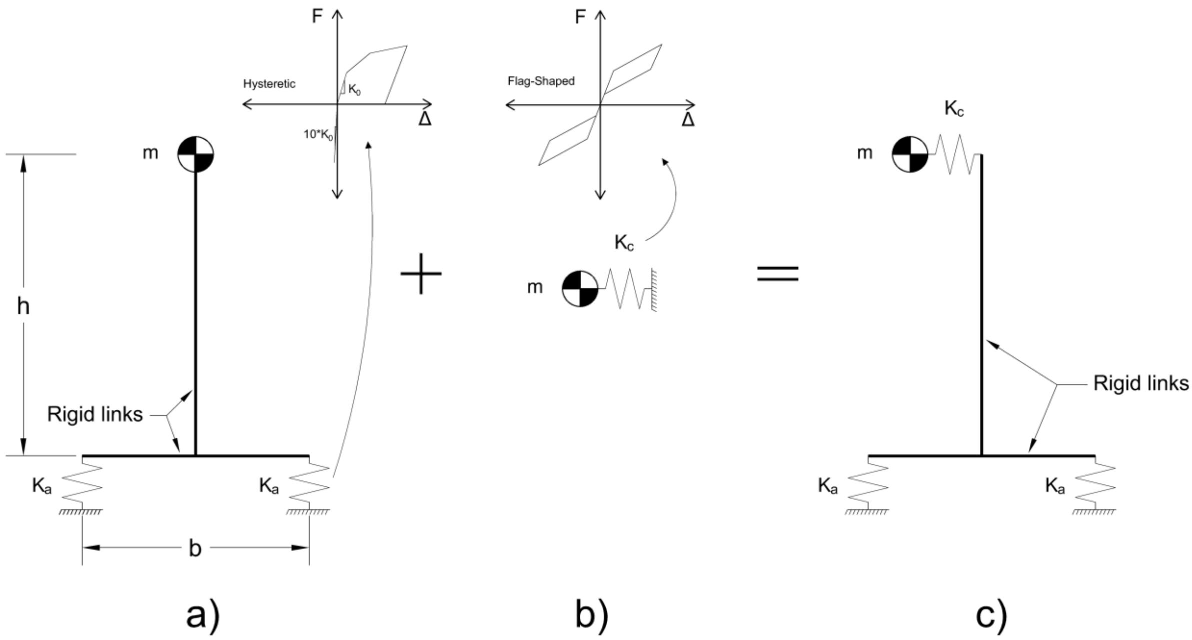


Figure 3. Modelling and calibration approach considered for the MDOF numerical model of the electrical cabinets.

For the calibration of the K_a non-linear springs, a compression stiffness one order of magnitude higher than the tension stiffness was considered, in order to simulate the vertical constraint provided by the base slab at which the specimens are connected. Rigid links are used to locate the mass *m* of the specimen at its center of gravity at a height *h* and a width *b/2* and recreate the overturning moment produced by the electrical cabinet mass distribution.

4 RESULTS

4.1 Single-degree-of-freedom model

The SDOF model was calibrated using 15 shake table tests of increasing intensity conducted during the experimental campaign. The input demand on the model consisted in the acceleration time-histories recorded at the base level of the shake table for each of the considered tests. The calibration was conducted individually for each of the selected tests, thus the damage accumulation experienced by the electrical cabinets due to the sequence of tests is not considered within this numerical model. Figure 4, Figure 5, and Figure 6 show the comparison between the absorbed energy time-history, the hysteretic response, and the relative displacement time-history documented for each of the selected tests from the experimental campaign against the prediction of the calibrated SDOF numerical model. The identification number assigned to each of the tests during the experimental campaign along with the corresponding peak test acceleration (PTA) are indicated for each of the tests used for the calibration of the numerical models. The numerical model is able to approximate accurately the absorbed energy and relative displacement time-histories. With respect to the hysteretic response, the numerical model underestimates the force experienced by the electrical cabinet during the selected tests from the experimental campaign. It is worth mentioning that applying a low-pass filter (at about 8Hz) to remove the high frequency content shown by the recorded acceleration time-histories, but absent in the recorded displacement time-histories, improves the accuracy of the inertial force estimate. The final calibrated parameters for the hysteretic material of the SDOF numerical model are listed in Table 1.

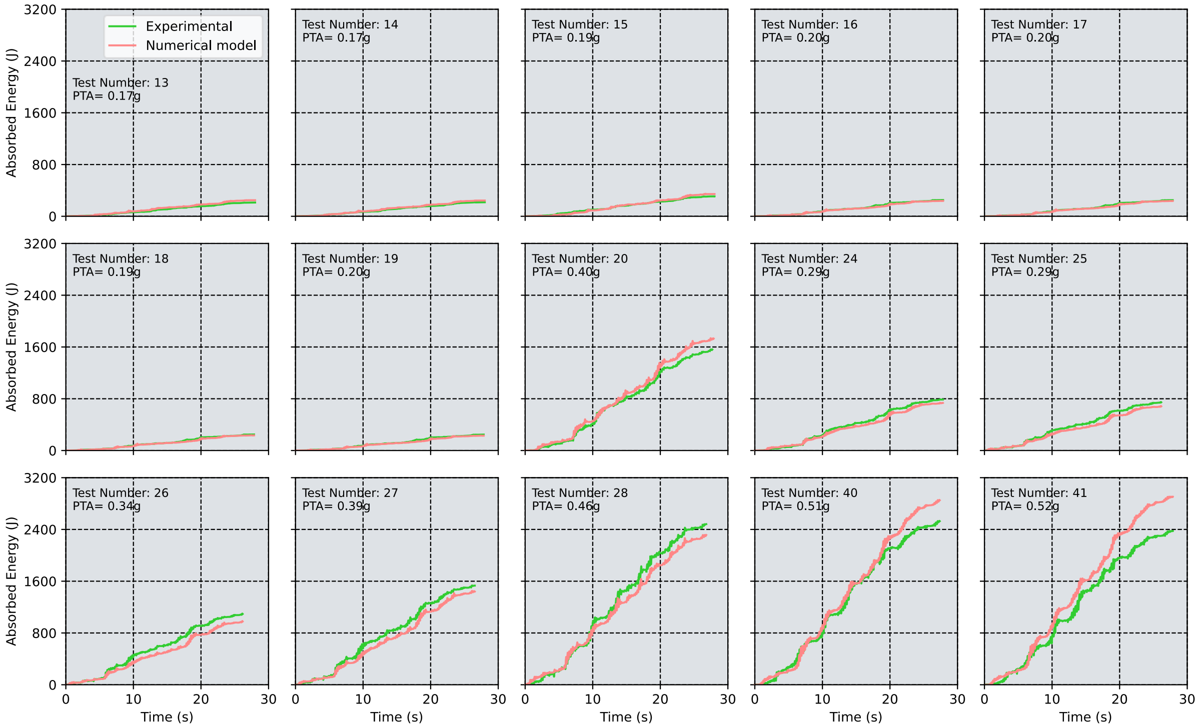


Figure 4. Comparison of the absorbed energy time-history of the electrical cabinet obtained during the experimental campaign against the prediction of the calibrated SDOF numerical model

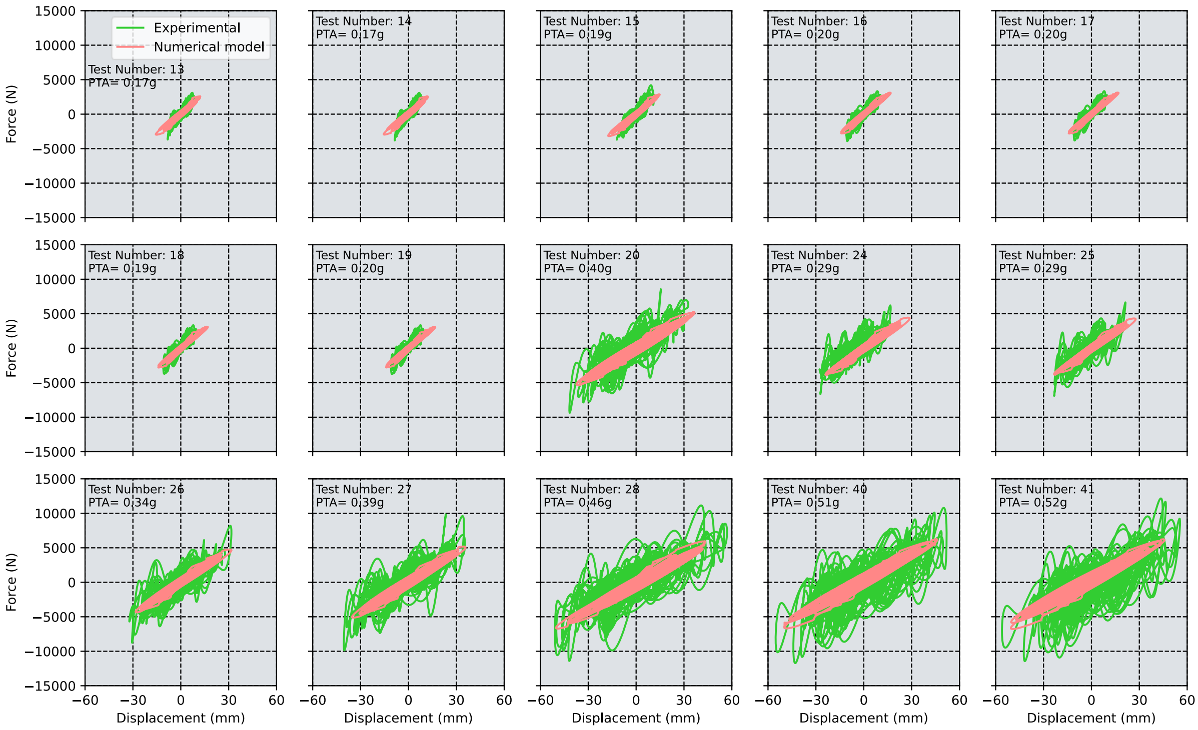


Figure 5. Comparison of the hysteretic response of the electrical cabinet obtained during the experimental campaign against the prediction of the calibrated SDOF numerical model

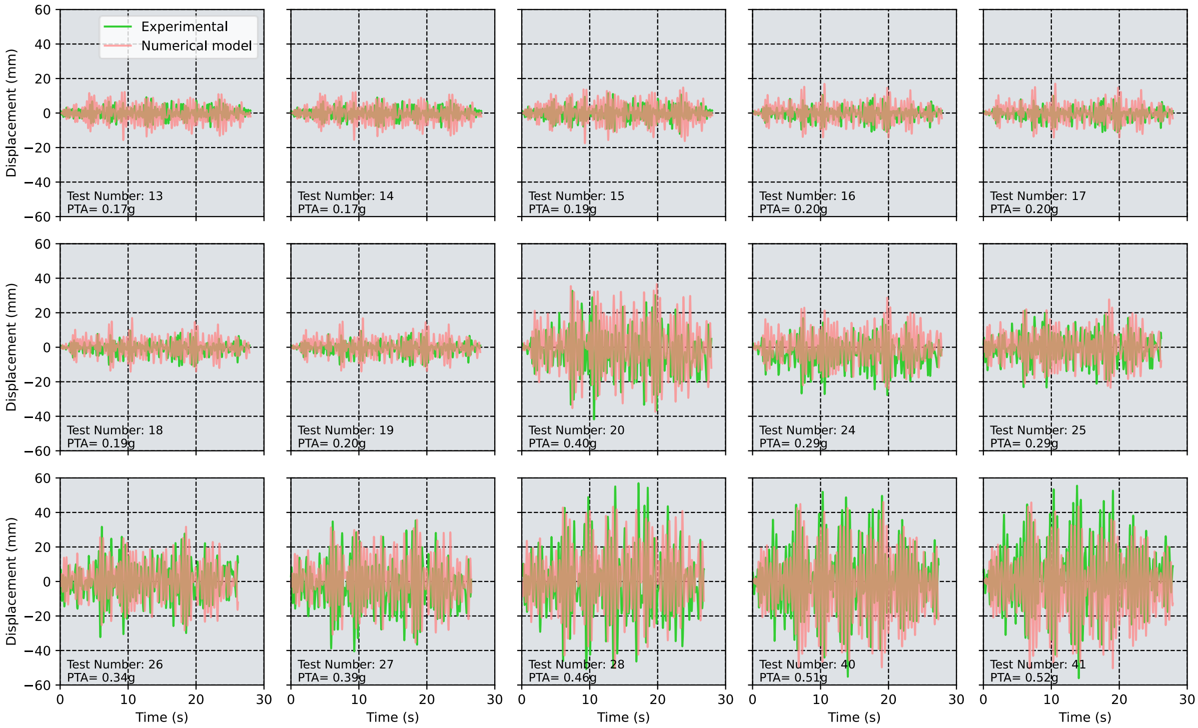


Figure 6. Comparison of the relative displacement time-history of the electrical cabinet obtained during the experimental campaign against the prediction of the calibrated SDOF numerical model

Table 1. Calibrated parameters for the *Hysteretic* material of the SDOF numerical model

Hysteretic (K_c)	
Parameter	***Value***
s_{1p}	0.35
e_{1p}	0.7
s_{2p}	2
e_{2p}	7
s_{3p}	6.68
e_{3p}	50.9
s_{1n}	-0.35
e_{1n}	-0.7
s_{2n}	-2
e_{2n}	-7
s_{3n}	-6.68
e_{3n}	-50.9
pinchx	1
pinchy	0.2
damage1	0
damage2	0
β_H	0.33
x_{Damp}	4.50E-02

4.2 Multiple-degree-of-freedom-model

For the calibration of the MDOF numerical model, the same 15 shake table tests used for the calibration of the SDOF numerical model were considered. In this case, the calibration was conducted by using the final state of the MDOF numerical model after each of the selected shake table tests, as initial conditions for the following shake table test, thus considering explicitly the damage accumulation in the electrical cabinets. Figure 7, Figure 8 and Figure 9 show the comparison between the absorbed energy time-history, the hysteretic response, and the relative displacement time-history documented for each of the selected tests from the experimental campaign against the prediction of the calibrated MDOF numerical model. The identification number assigned to each of the tests during the experimental campaign along with the corresponding peak test acceleration (PTA) are indicated for each of the tests used for the calibration of the numerical models. As for the case of the SDOF numerical model, the MDOF numerical model is also able to approximate accurately the absorbed-energy and relative displacement time-histories, while for the case of the hysteretic response, the force experienced by the electrical cabinets is underestimated. An improvement in the accuracy of the inertial force estimates is also observed for the MDOF numerical model when applying a low-pass filter (at about 8Hz) to the recorded acceleration time-histories. The final calibrated parameters for the *Hysteretic* and *SelfCentering* (flag-shaped) materials of the MDOF numerical model are listed in Table 2.

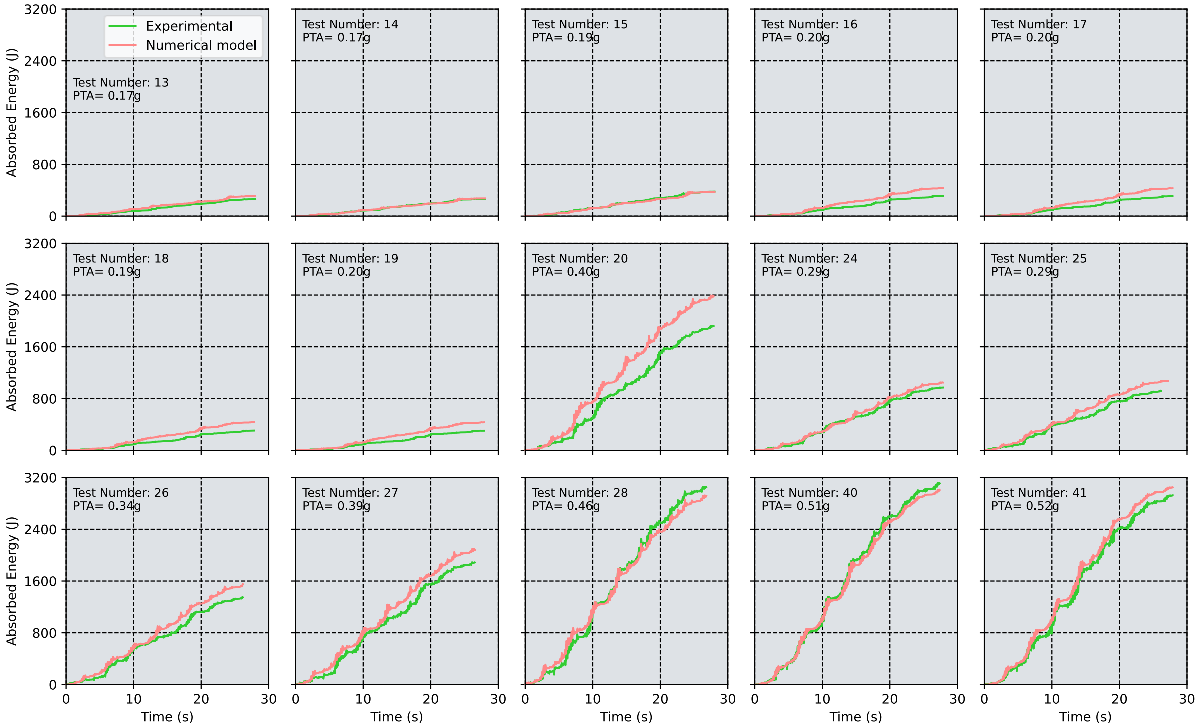


Figure 7. Comparison of the absorbed energy time-history of the electrical cabinet obtained during the experimental campaign against the prediction of the calibrated MDOF numerical model

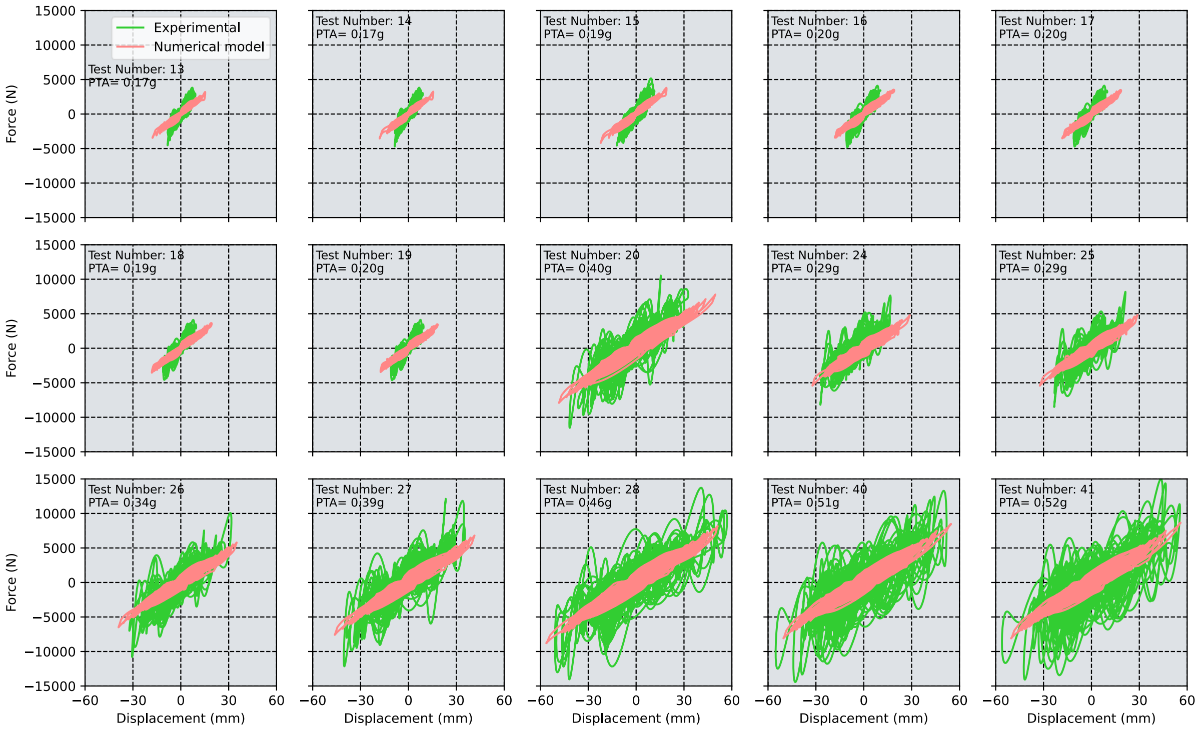


Figure 8. Comparison of the hysteretic response of the electrical cabinet obtained during the experimental campaign against the prediction of the calibrated MDOF numerical model

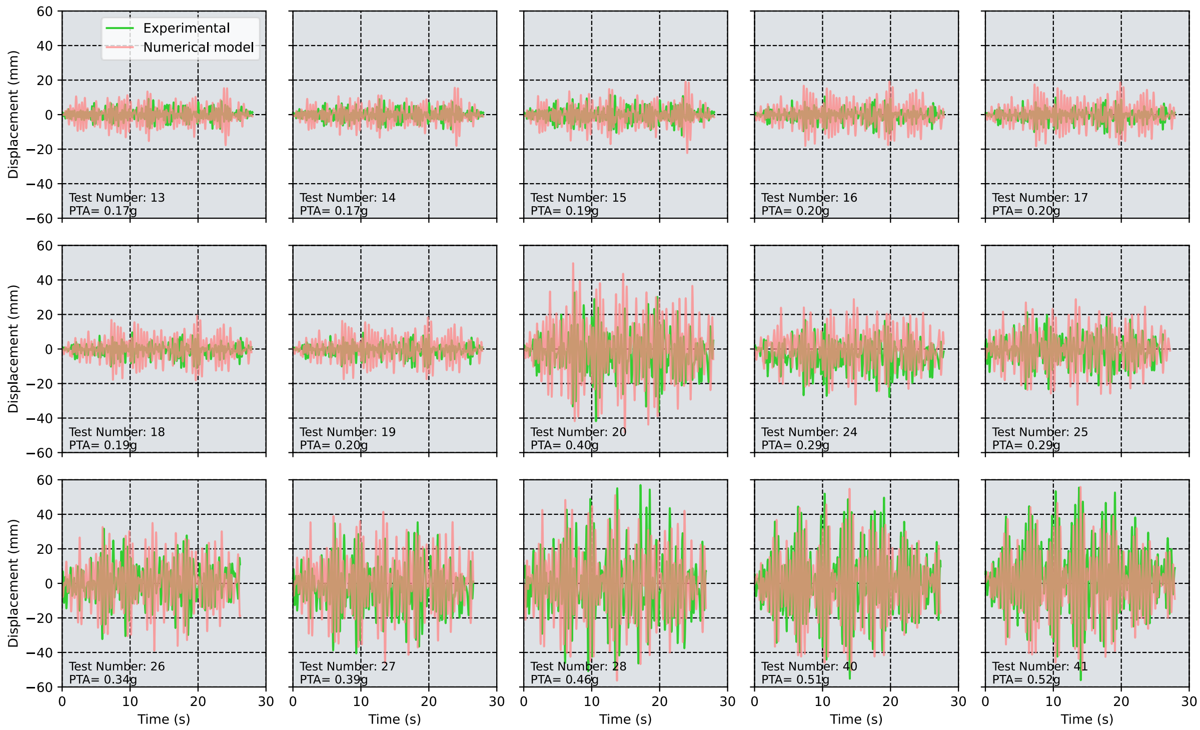


Figure 9. Comparison of the relative displacement time-history of the electrical cabinet obtained during the experimental campaign against the prediction of the calibrated MDOF numerical model

Table 2. Calibrated parameters for the hysteretic and self-centering (flag-shaped) materials of the MDOF numerical model

Hysteretic (K_a)		SelfCentering (K_c)	
Parameter	*Value*	*Parameter*	*Value*
s_{1p}	2.16	k_1	0.8
e_{1p}	2.2	k_2	0.3
s_{2p}	6.48	*sigAct*	0.85
e_{2p}	11	*beta*	1.3
s_{3p}	25.2		
e_{3p}	60.5		
s_{1n}	-21.6		
e_{1n}	-2.2		
s_{2n}	-64.8		
e_{2n}	-11		
s_{3n}	-252		
e_{3n}	-60.5		
pinchx	0.21		
pinchy	0.02		
damage1	0		
damage2	0		
β_H	0		

5 CONCLUSIONS

In this paper, numerical models were developed to predict the response of electrical cabinets based on the results from a shake table experimental campaign conducted in the 6DLAB laboratory of the Eucentre Foundation. One specimen from the experimental campaign was selected for the calibration of the models. Two different numerical models were calibrated: i) a single-degree-of-freedom (SDOF) system calibrated to match the relative displacement time-history, absorbed energy time-history, and force-relative displacement hysteretic response obtained during the experimental campaign, and ii) a mechanics-based multiple-degree-of-freedom (MDOF) system in which the calibration of the response of the specimen attachments and the specimen internal support structure were conducted separately, and then combined to recreate the relative displacement time-history, absorbed energy time-history, and force-relative displacement hysteretic response observed during the experimental tests. By comparing the experimental results with the numerical predictions, it was shown that the developed numerical models are able to accurately approximate the absorbed energy and relative displacement time-histories of the electrical cabinets when subjected to the input base accelerations from the shake table tests, while for the case of the hysteretic response, the inertial force experienced by the electrical cabinets is underestimated. Furthermore, the MDOF numerical model is able to capture the damage accumulation in the electrical cabinet as a result of the applied sequence of shake table tests.

The calibrated numerical models are useful to generalize the results obtained during the experimental campaign, and can be used to conduct additional numerical studies on the seismic performance of other configurations of electrical cabinets.

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