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Optimization of the Cyclic In-plane Response of Reinforced Concrete Frames with Infill Masonry Walls Using a Genetic Algorithm

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Abstract

A typical option in building construction is the use of reinforced concrete frame structures with infill masonry walls . The presence of infill walls in frame structures greatly influences the dynamic behavior of frame structures during seismic events. This wall usually does not have a structural role, being neglected in the design phase of building structures. Innumerous negative effects may arise from the neglection of this non-structural element in frame structures, namely, increased shear, energy, and ductility demands in the structure's elements, torsional effects due to irregular height or plan distributions of the infill panels in buildings, out-of-plane failure of the walls projecting debris to the inside or outside of the buildings, etc. Hence, this work intends to study the in-plane cyclic behavior of reinforced concrete portal frame structures with infill walls . A numerical model is developed to replicate the quasi-static experimental response of reinforced concrete frames with infill walls specimens. To obtain an optimal response , the corresponding model's parameters are calibrated through the use of a genetic algorithm . Results show that these algorithms can be a good option in calibrating the in-plane cyclic response of masonry infilled reinforced concrete frame structures.

Author keywords

Cyclic response ; Genetic algorithm ; Reinforced concrete frame structures with infill walls

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Optimization of the Cyclic In-plane Response of Reinforced Concrete Frames with Infill Masonry Walls Using a Genetic Algorithm

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Abstract. A typical option in building construction is the use of reinforced concrete frame structures with infill masonry walls. The presence of infill walls in frame structures greatly influences the dynamic behavior of frame structures during seismic events. This wall usually does not have a structural role, being neglected in the design phase of building structures. Innumerous negative effects may arise from the neglection of this non-structural element in frame structures, namely, increased shear, energy, and ductility demands in the structure's elements, torsional effects due to irregular height or plan distributions of the infill panels in buildings, out-of-plane failure of the walls projecting debris to the inside or outside of the buildings, etc. Hence, this work intends to study the in-plane cyclic behavior of reinforced concrete portal frame structures with infill walls. A numerical model is developed to replicate the quasi-static experimental response of reinforced concrete frames with infill walls specimens. To obtain an optimal response, the corresponding model's parameters are calibrated through the use of a genetic algorithm. Results show that these algorithms can be a good option in calibrating the in-plane cyclic response of masonry infilled reinforced concrete frame structures.

Keywords: Genetic algorithm · Cyclic response · Reinforced concrete frame structures with infill walls

1 Introduction

Reinforced concrete (RC) structures with infill walls are a construction typology that is largely used around the world. The understanding of the interaction between the frame structure and the infill is not straightforward since it depends on brick materials, mortar mechanical characteristics, brick geometry, the workmanship quality, the relative stiffness between the frame and the infill panel, etc. [1]. The vast experimental and analytical studies [2–4], and observations of the aftermath of seismic events [5], settled that the presence of infill walls in structures as non-structural elements under earthquake excitations influences the dynamic response of building structures, leading to both positive and negative effects.

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In general, the bare frame withstands vertical loads, whilst the frame and infill walls jointly carry the horizontal loads, with a prevalent truss action mechanism in the infills [1].

Subjected to lateral loads, infill walls usually react with the surrounding frame structure between the upper corner of the windward column and the lower corner of the leeward column, forming a compression-only diagonal. Under large deformations, the frame and the infill come in contact in these corner regions, designated by contact lengths, and detachment occurs in the remaining corners due to the deformation differences between these elements, leading to the diffusion of cracks at these interfaces.

This behavior led to the development of macro-models that considered an equivalent diagonal strut element (Fig. 1 and 2a), functioning only in compression, to model the presence and influence of infill walls in frame structures. This modeling approach has been evolving in such a way that can now account for a large number of physical phenomena, such as the failure modes expected in infill walls due to in-plane (IP) loads [6, 7], the relative infill-frame lateral stiffness [8], the consideration of openings in the infill panel and partially infill walls [9], shear failure of the columns [10], the influence of vertical loading [11], Out-of-plane (OOP) stiffness, strength and failure, and its interaction with IP loading [2, 12], non-linear inelastic behavior of the infill, and its application to structural systems with multiple stories and bays [3].

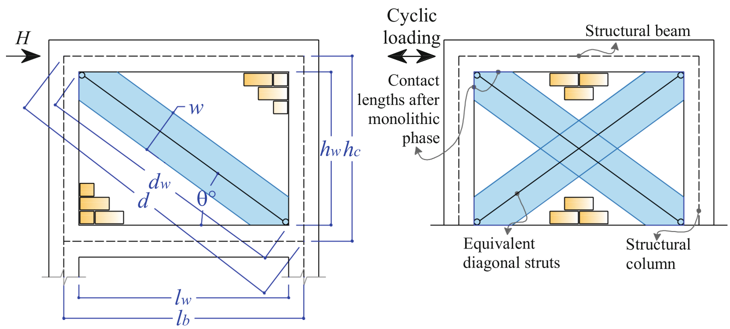


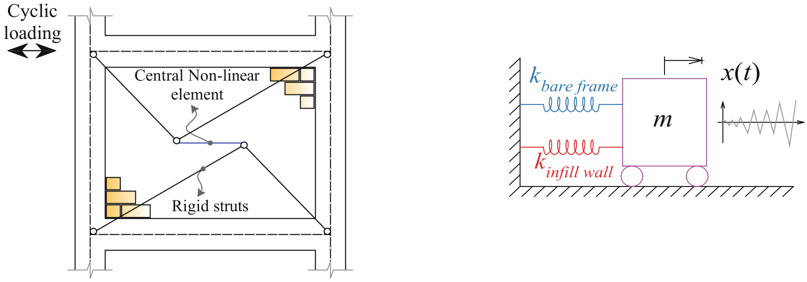
Fig. 1. Equivalent diagonal strut macro-modeling representation.

Hence, in this study, an equivalent strut macro-model is used to replicate the quasi-static cyclic response of RC frame structures with infill masonry walls. This modeling approach needs calibration of the parameters defining the degradation phenomena in the non-linear response of the structural systems. To do this a genetic algorithm (GA) is used to find an optimal solution to this problem by minimizing the normalized root mean square error (NRMSE) between the experimental and numerical responses. GAs have been employed and studied over the years to estimate parameters of non-linear hysteretic systems [13, 14] and optimal parameters of vibration control devices [15].

Results show that GAs show good performance in finding candidate solutions of numerical models that offer reduced errors compared with the observed data.

2 Numerical Formulation

The numerical models are developed in OpenSees [16] similar to the works of Furtado et al. [17] (Fig. 2a). This formulation may be related to the consideration of two non-linear springs in parallel, representing the frame and the infill wall (Fig. 2b).



(a) Beam-columns and truss elements. (b) Spring system.

Fig. 2. Schematic representations of the models used.

A study at the Laboratório Nacional de Engenharia Civil comprised 2:3 scaled RC portal frame structures with and without infill masonry walls under cyclic IP loads [4]. From this experimental campaign, four specimens were selected for analysis (Bare frame – M1; Frame with infills – M2, M3, M6). The geometrical and mechanical properties, and numerical models are briefly outlined in the next subsections.

2.1 Geometric and Mechanical Properties of the Specimens

The dimensions of the specimens and the displacement law applied are presented in Fig. 3. The mechanical properties of these specimens are summarized in Table 1.

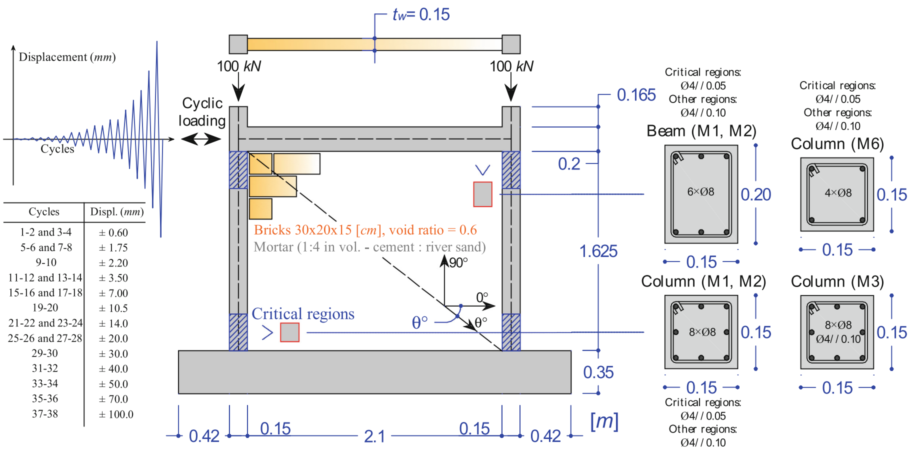


Fig. 3. Geometry of the specimens considered in this study and the displacement law.

Table 1. Mechanical properties of the materials used in the experimental campaign [4].

	Model	**Compressive strength, f_c (*MPa*)**	**Young's modulus, E_c (*MPa*)**
Concrete	***M1***	33.1	30000 (Assumed)
	M2	28.3	30000 (Assumed)
	M3	33.2	30000
	M6	35.2	30100
Steel reinforcement	**Diameter (*mm*)**	**Yield strength, f_y (*MPa*)**	**Young's modulus, E_s (*MPa*)**
	ø4 (Transverse)	523	200000
	ø8 (Longitudinal)	434	190000
Masonry wall	**Model**	**Mean compressive strength, f_{m90} (*MPa*)**	**Mean shear strength, τ_0 (*MPa*)**
	M2 and M3	2.1	0.27
	M6	2.5	0.51

2.2 Numerical Procedure

The model presented in Fig. 2a is composed of beam-columns for the structural elements and the rigid struts are truss elements. Plastic hinges were assumed at the critical regions of the columns, i.e., at their ends. The length of these regions is considered 0.30 m (Fig. 3). The center region of the columns is assumed as linear elastic. Rigid offsets were applied at the top of the columns equal to the beam's height. The beam was assumed rigid elastic since in the model the load device restricted the beam to deform during the experiment, preventing the development of plastic hinges. The central element, where the infill behavior is lumped is a two-node link element.

A uniaxial material property was assigned to each element as presented in Fig. 4. A confined and unconfined concrete material (*Concrete01* [18] and *ConfinedConcrete01* [19]), were assigned to the corresponding fibers. The longitudinal reinforcement follows the uniaxial material *Steel02*. The central element is a non-linear spring whose behavior is managed by *Pinching4* uniaxial material. In Fig. 4 all constitutive laws are defined for M2. The force-displacement relation of *Pinching4*, is presented without degradation. Calibration of its parameters will be the goal of the next section. The backbone curve is defined by cracking, yielding, maximum, and ultimate points (Fig. 5a). Cracking and maximum forces are, respectively, calculated as follows [6, 7]

$$V_{\max} = \min\left(\underbrace{\frac{2}{3} z t_w f_m \sec(\theta)}_{R_{DC}\,(\text{Diagonal compression})}, \underbrace{\frac{\tau_0}{1 - \mu (h_c/l_b)} t_w d_w}_{R_{ss}\,(\text{Shear sliding})} \right) \cos(\theta) \tag{1}$$

$$V_{\text{crack}} = 0.5\pi\, t_w d_w f_{tm} \cos(\theta) \tag{2}$$

where μ is the friction coefficient (=0.30), z is the contact length between the columns and the infill, and λ [8] is the frame-infill relative stiffness parameter, respectively,

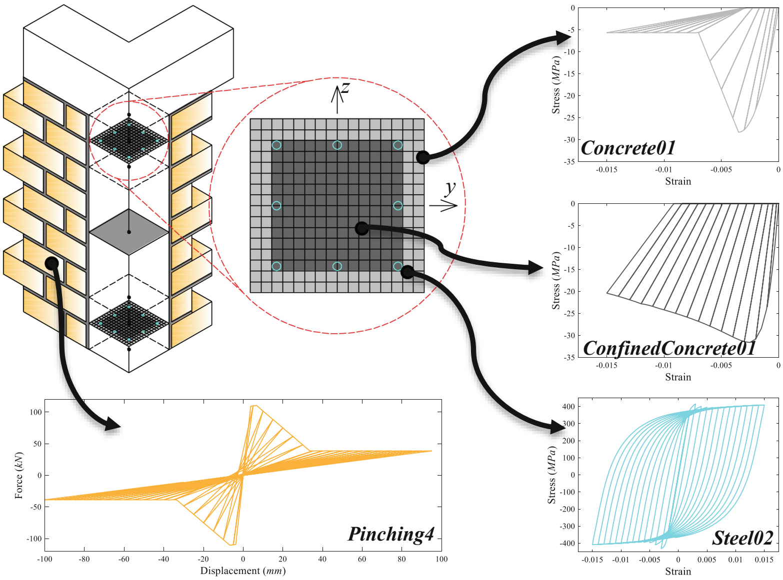


Fig. 4. Constitutive laws considered for each element of the specimen's M2 structural system.

$$z = \frac{\pi}{2}\frac{h_c}{\lambda} \quad \text{and} \quad \lambda = \sqrt[4]{\frac{E_{m\theta} t_w \sin(2\theta)}{4E_c I_c h_w}} \tag{3}$$

where f_{tm} is the tensile strength of masonry, assumed 5% of the f_{m0}, and f_{m0} considered as 50% of f_{m90} [20]. The Young's modulus of the masonry material along (E_{m0}) and orthogonal to the bed-joints (E_{m90}) were derived in function of the masonry compressive strength, and the shear modulus, G_{m0-90}, as $0.4E_{m90}$, implicitly assuming the Poisson's ratio, ν_{m0-90}, equal to 0.25 [21]. Assuming a homogenous orthotropic behavior for the masonry with directions coinciding with the horizontal and vertical directions (Fig. 3), the elastic properties can be derived along any direction (θ direction) [22]

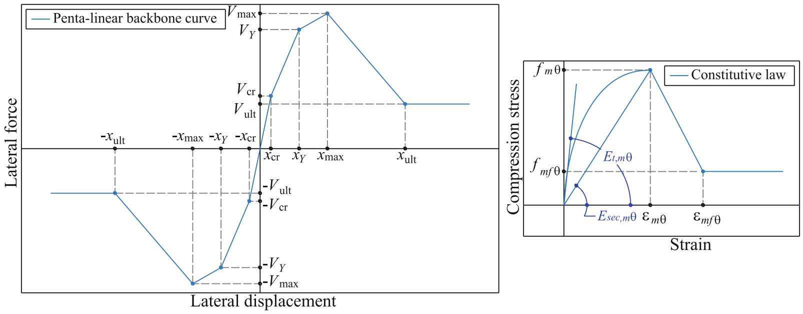
$$E_{m\theta} = \left\{ \frac{\cos^4(\theta)}{E_{m0}} + \left[\frac{1}{G_{m0-90}} - \frac{2\nu_{m0-90}}{E_{m0}} \right] \cos^2(\theta)\sin^2(\theta) + \frac{\sin^4(\theta)}{E_{m90}} \right\}^{-1} \tag{4}$$

Masonry compressive strength can now be determined along the diagonal direction by assuming linear proportion between the Young's modulus and compressive strengths' ratio: $E_{m\theta}/E_{m90} = f_{m\theta}/f_{m90}$ [23]. Considering the stress-strain relationship of unreinforced masonry in Fig. 5b, the maximum displacement, $x_{\max}$, can be determined [24]

$$E_{t,m\theta} = 2E_{sec,m\theta} \rightarrow E_{sec,m\theta} = f_{m\theta}/\varepsilon_{m\theta,\max} \rightarrow x_{\max} = \varepsilon_{m\theta,\max} d_w/\cos(\theta) \tag{5}$$

Having $x_{\max}$ then $V_{\max}$ can be determined with Eq. 1. With $V_{\max,}$ the initial lateral stiffness of the infill wall, k_{0w}, can be estimated by considering twice the ratio between the $V_{\max}$ and $x_{\max}$. The cracking displacement is computed with the values of V_{crack} and k_{0w}. The yield displacement, x_Y, is computed as an intermediate point between the cracking and maximum displacement [3]. The corresponding yield force, V_Y, is computed by assuming that the initial stiffness is reduced by a factor of a (assumed 0.01),

$$V_Y = (V_{\max} - ak_{0w}x_{\max})/(1-a) \tag{6}$$



(a) (b)

Fig. 5. Force-displacement backbone curve and constitutive law of the infill masonry wall.

Finally, the ultimate lateral force, V_{ult}, is assumed based on the observation of the experimental results as 35% of the maximum force for M2 and M3, and 40% for M6. The ultimate displacement, x_{ult}, will be the target of calibration within a user-specified range (between 3 and 10 times the maximum displacement). The values of the parameters defining each model are presented in Table 2. The maximum and ultimate ($\varepsilon_{c,unc}$) strains of unconfined concrete had to be adjusted so to better match the experimental results and avoid numerical instabilities. The confined concrete ultimate strain ($\varepsilon_{c,conf}$) was calculated based on the following empirical expression adapted from [18]

$$\varepsilon_{c,conf} = \varepsilon_{c,unconf} - 0.9\rho_s\left(f_{yT}/300\right) \tag{7}$$

Table 2. Calculated parameters of confined and unconfined concrete, and masonry materials.

$\varepsilon_{c,unc}$	$\varepsilon_{c,conf}$	x_{crack}	x_Y	$x_{\max}$	V_{crack}	V_Y	$V_{\max}$	$E_{m\theta}$	$f_{m\theta}$
					M2				
-0.007	-0.0155	0.790	3.752	6.715	25.977	109.339	110.455	1648.2	1.65
					M3				
-0.007	-0.0112	0.790	3.752	6.715	25.977	109.339	110.455	1648.2	1.65
					M6				
-0.007	-0.0155	0.681	3.698	6.715	30.925	150.952	152.493	1962.2	2.00

a. Displacement in mm; Force in kN; Strength in MPa.

3 Optimization Procedure

GAs are based on a natural selection process, resembling the process that drives biological evolution. A random population of individuals (solutions) is first defined. This population is changed at each generation by selecting individuals (parents) that will produce a new population (children – the next generation). The new generation is formed from the previous by using crossover and mutation rules that, respectively, combine two parents to form children and make changes to individual parents to create children. From generation to generation the population evolves towards an optimal solution. A GA-based approach is chosen to find the optimal parameters in this study over a simplex algorithm, since GAs are capable of searching among a big population for candidate solutions more rapidly, providing more control over the search. GAs' performance is, however, limited in finding the actual local or global optimum [13].

A script is used to link the OpenSees models to the built-in function in MATLAB [25] – *ga*, whose purpose is to find the minimum of an objective function using a GA. The objective function is the NRMSE between the numerical and experimental restoring forces. The normalization is performed concerning the range of the experimental restoring force. To define the rules of selection, mutation, and crossover, functions were chosen within MATLAB's GA options according to the problem under study. For the elite children, 5% of the population size was assumed. For selection, the tournament option was chosen, in which solutions are randomly selected from a group of 70% of the population, to compete and find the best solution as a parent. The rule of mutation chosen follows a random direction adaptive to the last successful or unsuccessful generation, satisfying bounds. The crossover function randomly combines solutions, within a user-specified fraction of the population (80% of the population). A flowchart is presented in Fig. 6 to illustrate the procedure used.

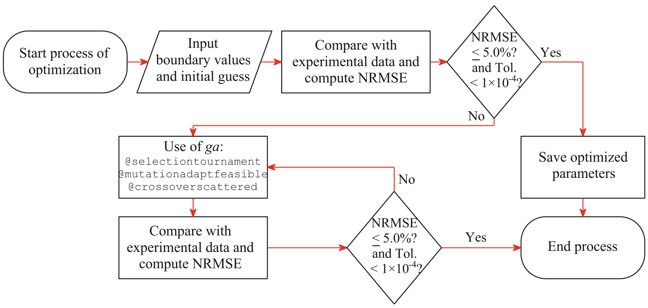


Fig. 6. Flowchart of the optimization process undertaken.

4 Results and Discussion

The optimization problem considered 23 variables, including the parameters of the *Pinching4* model and the ultimate displacements of the infill wall backbone curve in the positive and negative directions. An initial population size of twice the number of variables was considered since it provided a faster convergence to a solution. After 300 generations, solutions were obtained that satisfied the specified stopping criteria, which were at least an NRMSE less than 5.0%. Figure 7 presents the solutions obtained with the GA, except for Fig. 7a in which no optimization was necessary.

In general, it is verified that the numerical models developed can provide a reasonable estimation of the IP cyclic response of RC frame structures with infill masonry walls. Nevertheless, the numerical model seems to have some difficulties in replicating asymmetries in the cyclic response, as can be seen in Fig. 7c for specimen M3.

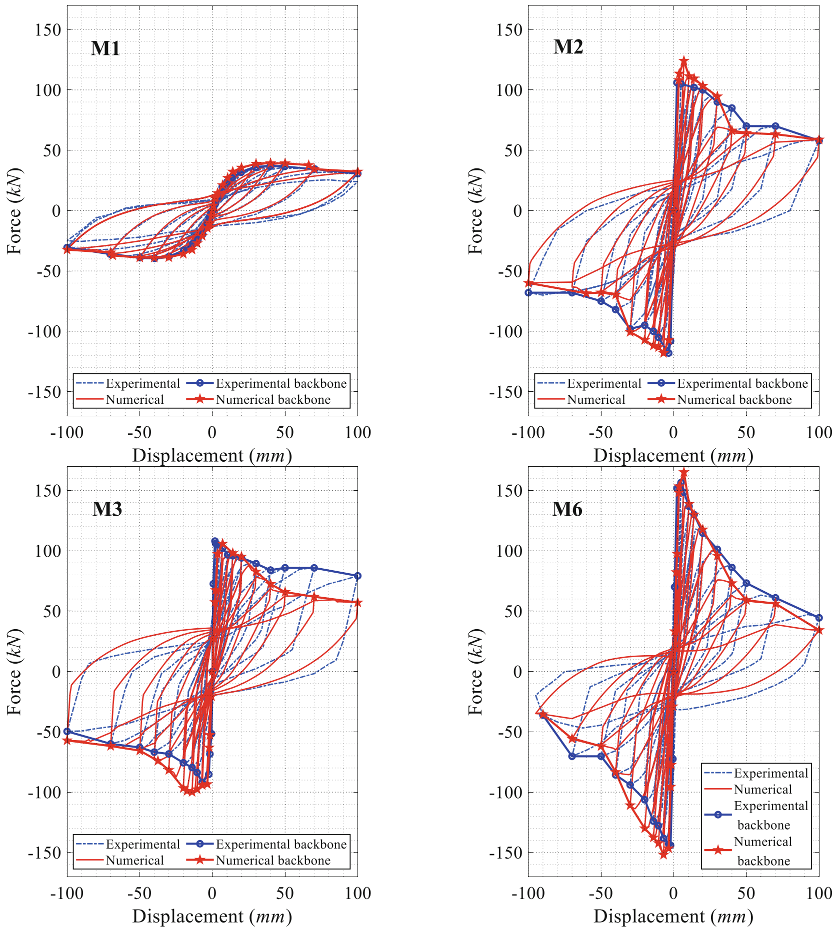


Fig. 7. Numerical results calibrated with experimental data.

Table 3 presents as an example the optimized parameters for specimen M2. The values reflect the adaptations of the numerical model to the actual cyclic response with degradation. In general, it can be verified more degradation in the first two phases (namely, between the cracking and maximum phases). Asymmetries are verified by

Table 3. Calibrated parameters of *Pinching4* in OpenSees [16] for the specimen M2.

M2							
rDispP	0.0574	***gK1***	1.7931	***gD1***	1.3563	***gF1***	0.3617
rForceP	0.3611	***gK2***	1.6270	***gD2***	1.0749	***gF2***	2.0000
uForceP	-0.2082	***gK3***	0.1794	***gD3***	0.9595	***gF3***	0.5715
rDispN	0.4156	***gK4***	1.4484	***gD4***	0.7756	***gF4***	0.4087
rForceN	0.7478	***gKLim***	0.5726	***gDLim***	0.7701	***gFLim***	0.4445
uForceN	-0.2673	***ePd4* [*mm*]**	48.7029	***eNd4* [*mm*]**	-67.1500	***gE***	100

the differences in the positive and negative directions of the pinching parameters and ultimate displacements. The optimized parameters reflect the degradation observed.

5 Conclusions

The overall IP cyclic experimental response is reasonably captured by the numerical models. However, response asymmetries can be difficult to capture. The optimization process was rather quick and the resulting parameters represented the level of degradation observed. Thus, GAs can be a good option in optimizing and calibrating the IP cyclic response of masonry infilled RC frame structures. Further developments should include GA-optimization of the OOP behavior and interaction with IP behavior.

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14:20 – 14:40	59	Optimization of the cyclic in-plane response of reinforced concrete frames with infill masonry walls using a genetic algorithm Authors: Pedro Folhento, Rui Carneiro de Barros and Manuel Braz-César Abstract: A typical option in building construction is the use of reinforced concrete frame structures with infill masonry walls. The presence of infill walls in frame structures greatly influences the dynamic behavior of frame structures during seismic events. This wall usually does not have a structural role, being neglected in the design phase of building structures. Innumerous negative effects may arise from the neglection of this non-structural element in frame structures, namely, increased shear, energy, and ductility demands in the structure's elements, torsional effects due to irregular height or plan distributions of the infill panels in buildings, out-of-plane failure of the walls projecting debris to the inside or outside of the buildings, etc. Hence, this work intends to study the in-plane cyclic behavior of reinforced concrete portal frame structures with infill walls. A numerical model is developed to replicate the quasi-static experimental response of reinforced concrete frames with infill walls specimens. To obtain an optimal response, the corresponding model's parameters are calibrated through the use of a genetic algorithm. Results show that these algorithms can be a good option in calibrating the in-plane cyclic response of masonry infilled reinforced concrete frame structures.
14:40 – 15:00	101	Dual Airflow Control Strategy for Floating Offshore Wind Turbine Stabilization using Oscillating Water Columns Authors: Fares M'Zoughi, Payam Aboutalebi, Irfan Ahmad, Izaskun Garrido and Aitor J. Garrido Abstract: This paper presents an airflow control strategy developed for Oscillating Water Columns (OWC) integrated in the barge platform of a Floating Offshore Wind Turbine (FOWT). The concept of the investigated platform combines a barge-based FOWT with OWCs to help reduce the undesired vibrations induced from waves and wind. Moreover, the OWCs are governed by a dual airflow control strategy design to reduce the platform pitch and tower top fore-aft displacement in order to help stabilize the FOWT platform. This objective is achieved by controlling the valves within the OWCs. The comparative study between the standard FOWT and the proposed OWC-based FOWT, based on the analysis of the free decay responses, shows an improvement in the platform's stability by reducing both the platform pitch and tower fore-aft displacement.
15:00 – 15:20	65	Vortex shedding effects due to wind action on the design of steel tubular towers Authors: Samuel Bastos and Rui Barros Abstract: This work addresses the effect of vortex shedding due to wind action applied to steel tubular towers of constant circular section and its consequence on the design verifications, namely top deflection and fatigue. The effect of vortex shedding and fatigue were studied according with different methods available in the bibliography, in particular the Eurocode and CICIND model code methods [1]. Additionally, a simplified method based on a dynamic analysis and a physical interpretation of the phenomenon was developed and pro-posed. The methods studied were then applied to real structures, whose structural performance had been monitored over time. The estimates of the methods were compared with the measurements of the monitoring with the objective to evaluate the reasonableness of their application.
15:20 – 15:40	8	Distributed Predictive Policies for Local Residential Energy Communities Authors: Joaquim Palma Silva, José Manuel Igreja and João Miranda Lemos Abstract: The main goal of this work is to design Battery Storage Management solutions for Smart Grids with multiple interconnected microgrids, or local power generation units, using a distributed model predictive control approach. In order to know how much energy should be stored, sold or bought, a model predictive control policy computes the minimum of a cost function that minimizes the net revenue. The solution also encourage some level of storage. The alternating direction method of multipliers computes the proposed distributed model predictive control solution, considering that each system is directly interconnected with its neighbors. The distributed predictive control algorithm is described and tested in simulations.

15:40 – 16:00		Coffee break	
16:00 – 17:20	**ThA3**	**Networked and multi-agent control systems** *Chairs: Anikó Costa and Cristina Nuevo-Gallardo*	Room A