Numerical simulation method for masonry partition walls affected by the deflections of concrete structures

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Abstract. Non-structural masonry walls can be damaged when submitted to in plane loads, imposed by the vertical deflections of their support structures (e.g., concrete slabs). Given the high complexity of this problem associated to the masonry anisotropy and behavior of wall/structure interface joints, including the difficulty of reproducing real scale prototypes for laboratory testing, the use of more generalized and time efficient models are important aspects to be considered. Therefore, a numerical simulation method and its application is presented to simulate this type of problem. This method is based on a FEM macro-model, which includes a constitutive damage model for concrete calibrated for masonry walls and a shear-cohesion model to simulate the interface joints. This method was simulated in a case study of a masonry partition walls loaded by the vertical deflections of adjacent concrete structure. Results obtained highlighted a high risk of damage in the masonry partitions when these are loaded by the structural deflections limits referred in technical literature, especially if no detachment/movement partition/structure joints and no reinforcement techniques are used.

Keywords: simulation method, masonry partitions, concrete structures.

1 Introduction

According to CIB [1], most of the residential buildings in Europe have been made with reinforced concrete framed structures (piles, beams and slabs) filled with non-structural masonry walls (partitions and enclosure). In Portugal around 67% of buildings were constructed since the late 60s with this construction technology according to an INE [2] survey. Pereira [3] refers that the concrete slabs are typically made with lightweight systems (beam-and-block and flat waffle slabs), and the spans usually vary between 5m and 7m. The traditional solution used for partitions in Portugal are single leaf walls made with hollow low-density ceramic units (i.e., with horizontal percentage of voids of 60%) laid on general-purpose cement-based mortar joints, and partitions are bonded to the concrete structure with mortar joints made around the walls. Therefore, these partitions are fragile and low deformation capability elements that can be easily damaged when loaded by their supporting slabs, as it been the case in last 3 decades in Portugal, where cracking in masonry partition walls associated with an excessive vertical deflection of concrete slabs has been frequently reported in buildings in serviceability conditions.

To avoid damaging partitions some design measures are recommended by CIB [1] and CEN [4], such as controlling the maximum vertical deflections of structural elements and some construction provisions for the partition walls. The referred maximum deflections include the long-term creep effects and vary between L/500 and L/1000, depending on the span of the structural elements (L), on the existence of openings and on the use of preventive provisions to avoid cracks in the walls (e.g., mesh reinforcement renderings, use of detachment/movement joints to make partitions independent from the structure, amongst others).

As for numerical and experimental methods, the analysis of masonry structures can be made through advance numerical simulations or laboratory testing. However, both of these methods can be a difficult task, since the numerical approach may involve the simulation of the non-linear anisotropy behavior of masonry and the interaction between walls/support structure, and in the case of the experimental method difficulties may arise when reproducing real size prototypes of walls interacting with structural elements for laboratory testing. Testing masonry walls with reduced dimensions may be a viable option, however reduced scaled elements may not always reproduce the behavior of real size walls, since, according to the work of Knox [5], Milani [6] and Mohammed [7], the strength, stiffness and deformation in compression or in tension/shear will increase when using scales lower than 1:2, especially when closer to failure. Moreover, the referred half scale was found to have minimal effect on the compressive strength and stiffness of masonry, having, however, a more significant effect on the shear modulus and strength.

Regarding numerical methods, the main modelling strategies for studying the mechanical behavior of masonry constructions are based on the finite element method (FEM) and the discrete Element Method (DEM), and, according to Lourenco et al [8] and D'Altri et al [9], can be summarized as: - micro modelling, where the constituents of the masonry are modelled individually; - macro modelling with the masonry constituents transformed into a single composite material, or with multi-scale techniques where mechanical parameters of meso-scale elements (e.g. walls) are used in larger-scale or macro-scale elements (e.g. entire buildings). In both strategies, a block-based model based on the discrete Element Method (DEM) can be used, where the masonry walls are modelled with rigid or deformable units and/or joints using a mesh of finite elements connected by contact models that represent the frictional/cohesive behavior of joints or block/joints interfaces. Nevertheless, continuous and homogeneous FEM based models are the most used in the analysis of masonry walls, using equivalent constitutive laws of distributed cracking or elastic-plastic damage models or using homogenization techniques based on the concept of strain potential energy.

The choice of the best suitable modelling technique for masonry depends on the specific objectives of the analysis, the level of detail required, and on the available computational resources. In many cases combining modelling techniques may be used to balance accuracy and efficiency, such as using a continuum FEM with DEM.

Therefore, considering the persisting problem in Portugal of masonry partition walls being damaged by the vertical loading induced by deflections of concrete floor slabs, it is important to study more suitable deflection limits for slabs to ensure the best compatibility and less risk of damage in the masonry partitions. However, given the difficulty of reproducing real scale walls in laboratory testing for validation of deflection limits, the use of numerical simulations containing constitute models calibrated with experimental data can be a viable option.

In this paper a two-step numerical method partially calibrated with experimental results was used in a case study of masonry partitions loaded by concrete slabs. The main objective was to obtain structural deflection limits that are more suitable to the most common type of partitions used in Portugal, including the use of detachment joints and reinforced coatings.

2 Numerical simulations

2.1 General aspects

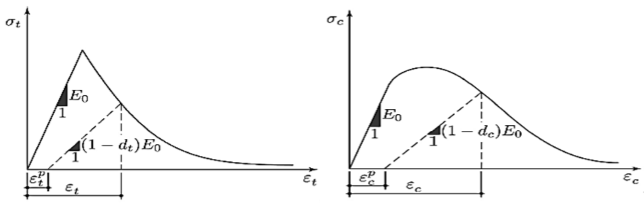
A 2-step method is proposed for the numerical simulation of partitions loaded by their supporting slabs. The method consists of the following main aspects: - Numerical assessment of the deformation/strength capability of a masonry partition acting as loaded beam, using a 3D FEM macro model with a nonlinear damage plasticity constitutive model proposed by Lubliner et al [10], calibrated with experimental data obtained from lab tests performed on relatively small masonry walls; - Numerical assessment of the behavior of partitions loaded by the deformation of a real size concrete structure, using FEM and DEM coupling with a fiction/cohesive contact model to simulate the interaction between the partitions and the concrete structure.

This simulation method was used in case study, where the most common solutions used in Portugal for building structures and partitions walls (with or without reinforcement) was considered: - Traditional partition walls made from lightweight clay hollow units (60% of voids and 15cm of thickness) laid on joints made with general purpose cement-based mortar (GP); - Same partitions as above, however with 2cm thick reinforced coatings applied on both faces of the walls, made with a stronger GP mortar (the same mortar used for the masonry joints) and reinforced with 2 different types of glass fiber mesh (GFM1 – coating reinforced with a more open/weaker mesh, GFM2- coating reinforced with a denser/stronger mesh), with the objective of improving the strength and deformation capability of the masonry partitions; - Reinforced concrete Structure (RC) made with piles, beams and lightweight slabs (beam-and-block floor system), designed according to Eurocode [4],[11],[12] for residential/commercial buildings.

2.2 Numerical assessment of the deformation/strength of partition walls

The masonry partition walls were simulated with a 3D FEM model based on an 8 node linear brick elements (C3D8R) meshing, without discretization units, joints and renderings, therefore using homogenized-material model for unreinforced and reinforced partitions. These partitions were simulated as beams loaded with in-plane vertical forces in order to obtain strength and displacements values.

The chosen constitutive model for masonry is a non-linear plastic damage model developed for concrete by Lubliner et al [10], and can be used for other brittle or quasi-brittle materials whose fracture mechanism are mainly governed by compressive crushing and tensile cracking (e.g., masonry, mortars). These fracture mechanisms are implemented in the model through uniaxial tensile and compressive stress-strain relationships (σ_t - ε_t and σ_c - ε_c) obtained from available experimental data. The fracture mechanisms are simulated in the model with the degradation of the initial stiffness/elasticity modulus (E_0), using tension and compression damage parameters (dc, dt) that are established as a function of the tension and compression plastic extensions ($\tilde{\varepsilon}_t^{pl}, \tilde{\varepsilon}_c^{pl}$). The stress-strain relationships can be obtained from experimental results of uniaxial tensile and compressive tests and the damage parameters can be estimated as the ratio between the initial yield strength and the applied stress level (if no experimental data aren’t available from cycling tests). The stresses are then calculated as effective compressive and tensile stresses ($\sigma_{c,eff}$, $\sigma_{t,eff}$), Fig.1. The yield behavior is based on “Drucker-Prager” plastic flow rule, effective stresses and plastic extensions, where is possible to adjust some dimensionless parameters to calibrate the non-linear response of the model. More specific details of this model and its application to masonry assemblies can also be found in the work of Sousa et al [13] and Rainone et al [14].



$\sigma_{t,eff} = (1 - d_t)E_0(\varepsilon_t - \tilde{\varepsilon}_t^{pl})$ $\quad$ $\sigma_{c,eff} = (1 - d_c)E_0(\varepsilon_c - \tilde{\varepsilon}_c^{pl})$

Figure 1. Generic tensile and compressive stress-strain relationships for calculation of effective compressive and tensile stresses in the constitutive model

To calibrate the constitutive model chosen for the partition walls, some experimental data obtained from compressive and flexural tests performed on relatively small masonry wall samples were used. The calibration was made through the simulation of the flexural tests performed in laboratory.

For the compressive behavior, labs tests were performed according to CEN [15] on small scale masonry walls in the parallel direction of the masonry horizontal mortar joints, Fig.2. Nine test samples of traditional clay masonry were made with the dimensions of 0.8m x0.8m x0.15m (height x width x thickness). Three samples were made without coatings (UM), and six with 2cm thick mortar coatings reinforced with 2 different types of glass fiber mesh (RM-GFM1 - masonry with the coating reinforced with an open/weaker mesh, and RM-GFM2 - masonry with the coating reinforced with denser/stronger mesh). The main proprieties obtained for the masonry samples, including other experimental data obtained for masonry units, mortar and fiber mesh, are presented in Tab.1 and Fig.5.

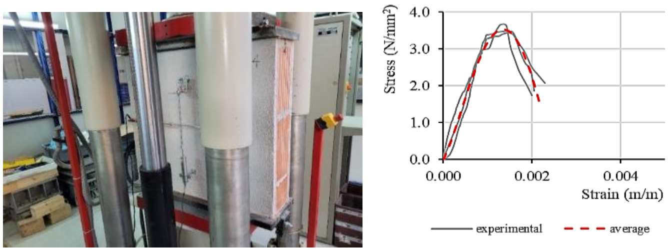


Figure 2. Example of the compressive test set-up and stress-strain obtained for masonry samples (RM- GFM1)

Table 1. Main properties of materials used in the small partition walls (average values)

Material		Initial elasticity modulus (N/mm^2)	Compressive Strength (N/mm^2)	Compressive Strain (-)
Masonry	UM	2885	3.1	0.0028
	RM-GFM1/GFM2	3745	3.5	0.0014
Mortar (joints and coatings)		8900	10	0.0019
Units		-	4.3	-
Material		**Tensile force (N/mm)**	**tensile strain (-)**	**Mass (g/m^2)**
Fibre mesh	GFM1	25.2	0.037	110
	GFM2	83.5	0.039	330

Regarding the tensile behavior, since direct tensile testing on masonry samples are hard to perform due to several practical reasons, flexural tests were performed instead on relatively small masonry partition walls. However, the dimensions of these samples were considered big enough to expect no significant differences between flexural and direct tensile behavior. Therefore, 3 experimental walls with length of 3.3m, height of 1.6m and thickness of 0.15m were tested with the same masonry and reinforced coatings mentioned in the compression tests. One wall was tested without coatings (UMW) and two walls were tested with reinforced coatings (RMW-GFM1 - wall with a coating reinforced with an open/weaker mesh and RMW-GFM2 - wall with a coating reinforced with a more dense/stronger mesh). The flexural test-up used was a simple supported wall with a span of 3.0m, loaded with a hydraulic jack applied on middle span of the wall. Several linear transducers (LVDT) were installed in the perimeter and in the surface of the wall to measure vertical displacements and internal deformations, Fig.3. The tensile stress and strains near the base of the walls was obtained from these flexural tests, and were implemented in model, with the tensile stresses calculated according to the elasticity theory for bending stress in rectangular sections, Fig.3. Moreover, initial cracking loads (i.e., loading that causes cracking visible to the naked eye) were obtained from these tests through filming and loading-time data to correlate cracking loads and displacements (Fcrack, dcrack). This allowed to estimate the initial cracking loads or displacement in the simulations, obtained as the ratio between initial cracking and failure loads or displacements (Fmax, dmax), Tab.2.

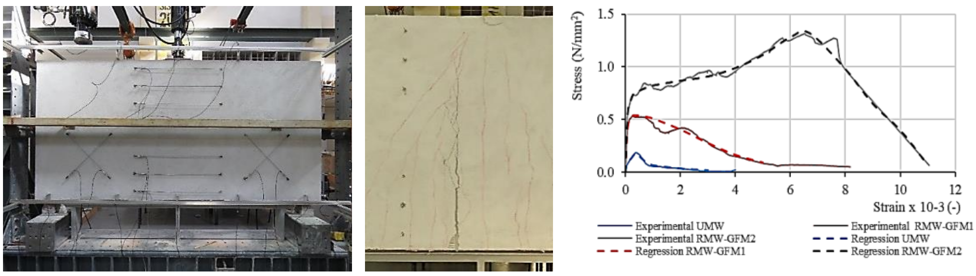


Figure 3. Example of the flexural test, fracture pattern and stress-strain for small partition walls (RMW-GFM2)

Table 2. Main results obtained from flexural lab tests performed on small partition walls

Type of wall	Displacements		Forces		Fcrack/Fmax	Stress	
	d crack (mm)	d max (mm)	F crack (kN)	F max (kN)	(-)	crack (N/mm^2)	max (N/mm^2)
UMW	0.36	0.60	16.0	16.2	0.99	0.19	0.19
RMW - GFM1	0.68	0.69	57.9	58.8	0.98	0.53	0.54
RMW - GFM2	1.65	5.67	90.0	144.1	0.62	0.82	1.32

Regarding the calibration of the constitutive model, this process consisted in obtaining the best fit between the numerical and experimental vertical forces and displacements, through the modification of the non-linear parameters of the constitutive model when performing numerical simulations of the real flexural tests made in laboratory. The model was considered accurate and representative enough to be used in the simulations, since the differences between experimental and numerical cracking and failures forces or displacements were low (ranged from 2% to 12%), and the numerical and experimental fracture pattern were considered similar, Fig.4.

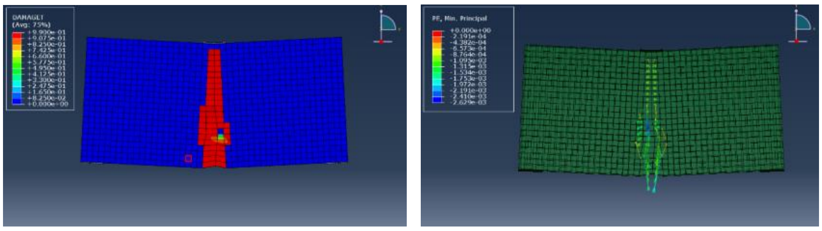


Figure 4. Example of the range and fracture pattern obtained in simulations of the UMW small partitions (damage variables and principal compressive plastic strains)

The calibrated constitutive model was then used to simulate larger/real size walls, i.e., reference walls UMW, RMW-GFM1 and RMW-GFM2, with the dimensions of 2,8mx 5,7m x 0,15m (height x length x thickness), which are to be loaded with the deflections of a real scale concrete structure (next step of the numerical method). This model was also used to obtain cracking and failure forces and displacements, determined from the simulation of a simply supported partition beams subjected to a uniform distribution law of vertical displacements ($\delta_{(x)}$), eq. (1), applied on the top of the partition walls to simulate the load resulting from displacements of slabs /beams:

$$\delta_{(x)} = \frac{1}{k}\frac{16\,(x^3 - 2L_s x^2 + L_s{}^3)}{5\,L_s{}^3}x \tag{1}$$

where L_s is the span of the wall (5.7m) assumed equal to the span of the structure, $1/k$ is the maximum relative deflection to be considered (e.g., 1/1000), and x is the considered position on the top of the wall (e.g., 0 to 5.7m).

2.3 Numerical assessment of the behavior of partitions loaded by a real size concrete structure

The coupling of a 3D FEM and DEM macro-models was used to simulate the masonry partition walls interacting with a real size concrete structure. The mesh used for partitions and concrete structure was based on 8 node linear brick elements (C3D8R), and to reduce the computation effort a trunked part of the building structure was simulated, since symmetry conditions allowed restraining the translations in XY directions, Fig.5. The concrete structure (i.e. a framed building structure with slabs, piles and beams) was designed according to Eurocode/CEN methodology [4],[11],[12] to accomplish displacements lower than L/500 (with creep effects) and to respect the recommended span/depth ratios for a quasi-permanent combination of actions/loads defined for serviceability conditions.

As mentioned, reference/real size masonry partition walls were simulated with and without reinforced coatings. All partitions walls were simulated bonded to the concrete structure in two different conditions: - Top and bottom bonding joints, and 2 movement/detachment joints with 1 cm wide at both sides of the partitions to avoid direct contact with the piles (lateral movement); - One bottom and two lateral bonding joints, and one movement/ detachment joint with 1cm wide at the top of wall to avoid direct contact with the slab (top movement).

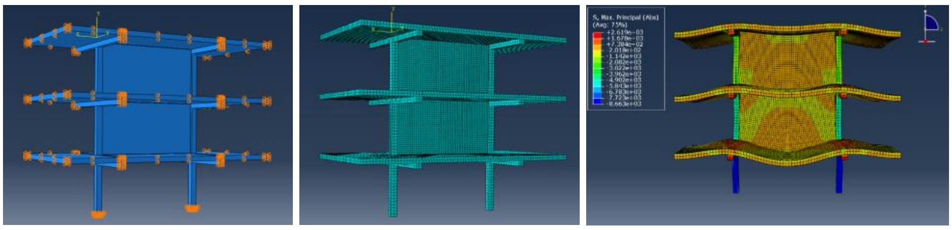


Figure 5. Symmetry conditions, meshing and stress distribution of the real size concrete structure and partitions

As for the constitutive models, the calibrated non-linear model was used for the reference masonry partition walls, and a linear elastic behavior was considered for the concrete structure, since the loading intensity is usually low for serviceability conditions, and uncracked sections can be assumed. To simulate the interaction between structure and partitions, interface joints were simulated with a linear shear-friction/ shear-cohesion contact model (Mohr-Coulomb with shear cut-off), assuming that this interaction was conditioned by the unit/mortar shear or bonding strength, Fig.6. To improve the accuracy, some experimental data was used in the contact model, which was obtained from shear tests on triplets and from pull-of tests performed according to CEN [16], [17], using units/mortar joint samples made with the same traditional masonry as the one used for the compression and flexural tests, Fig.6. The main objective of these tests was to obtain the initial shear strength, friction angle and the bonding/tensile strength between mortar joints and masonry units.

Figure 6. Representation of the contact model for the partitions/structure interface (including average values obtained from bonding -above- and shear triplet tests)

The creep effects on the concrete structure and masonry partitions were implemented in the simulations according to the calculation methodology of CEN [4] [18]. This methodology assumes that the creep on concrete only affects the strains, produces a viscoelastic behaviour for stress levels lower than 40% of the compressive strength, and affects the tensile behaviour in a similar way. Considering the service life for ordinary building structures (t= 50years), creep coefficients were obtained for the concrete structure ($\varphi_{(t)}$ = 2.2 and 2.5 for slabs and beams). An effective elasticity modulus, E_f, was implemented in the model to consider the creep effects in simplified way for the concrete structure, based on the initial elasticity modulus, E, after 28 days of curing (E_f = E/ (1+($\varphi_{(t)}$). The same conditions were assumed for the creep effects on the masonry partitions. However, for the masonry with mortar coatings, the mortar creep effects are expected to be similar to the concrete, therefore the creep coefficients and deformations are expected to be higher than masonry. To avoid complexity associated to the discretization of masonry and mortar layers, a more conservative and simplistic approach was assumed for the homogenised model of the masonry partitions, i.e., the creep effects on the mortar coatings and masonry was considered the same. Therefore, for the partitions an average value for the long-term creep coefficient ($\varphi_{(t)}$= 1) was assumed, based on the infinite creep coefficients defined in CEN [18] for clay masonry ($\varphi_{(t)}$ varies from 0.5 to 1.5). The creep strains were calculated and then added to the initial strains obtained for the uniaxial constitutive laws of masonry.

3 Results Analysis and Conclusions

For the simulation of the UMW and RMW larger/reference partitions beams, initial cracking and failure stresses and relative displacements (d/L – vertical deflection to span ratio), with and without long creep effects, are presented in Table 3. For the simulations of these partition walls interacting with the concrete structure with creep effects and movement joints, the main results obtained are presented in Table 4 for the relative displacements (d/L) and tensile stress levels for the concrete structure and relative displacements,

Table 3. Reference/larger partition wall beams (with long-term creep effects)

Type of wall	Tensile stress		Vertical displacements d/L creep	
	cracking (N/mm^2)	failure (N/mm^2)	cracking	failure
UMW	0.19	0.20	1/2423	1/2154
RMW-GFM1	0.53	0.54	1/1913	1/1675
RMW-GFM2	1.05	1.33	1/1411	1/244

Table 4. Reference/larger partition walls interacting with the concrete structure (with long-term creep effects)

Type of partition wall	Structure (slabs)	Partition walls			
		Lateral movement joints		Top movement joints	
	d/L creep	d /L creep	Tensile stress range (N/mm^2)	d /L creep	Tensile stress range (N/mm^2)
UMW	1/1000 to 1/1150	1/1515	> 0.19 (Cracking)	1/2447	< 0.19 (No cracking)
RMW-GFM1	1/1250 to 1/1406	1/1894	< 0.53 (No cracking)	1/2992	< 0.53 (No cracking)
RMW-GFM2	1/1350 to 1/1485	1/2045	<1.05 (No cracking)	1/3160	< 1.05 (No cracking)

The results obtained in the simulation larger/reference partition beams creep revealed that there's an improvement of strength and deformation capability when using partitions with reinforced coatings made with relative strong GP Mortars a GFM meshes, highlighting the case of stronger/denser GFM mesh (at the cracking point RMW-GFM2 partition is 72% more deformable and 5.5 times stronger than URW partition).

Concerning the results obtain for the simulation of partition walls interacting with the concrete structure, some aspects can be highlighted: - The relative deformation (d/L) of the concrete structure is equal or lower than the recommended of 1/1000 (e.g. in the simulations d/L of slabs ranged from 1/1000 to 1/1485), with the stresses lower than the tensile and compressive strength of concrete (i.e. structure within linear elastic regime or uncracked sections, as assumed in the simulation model); - The partitions are less deformable than slabs, especially when using movement joints on the top of the partitions (the ratio partition /concrete slabs defections ranged from 0.47 to 0.66, being 0.47 for the case of partitions with top joints); - The use of strong reinforced mortar coatings on partitions walls can also decrease the structural deformations of slabs (e.g., reduction of 25 % to 50% when comparing slabs supporting RMW with UMW partitions); - Except for the case of URW partitions with 2 lateral joints and 2 top/base bonding joints, all partitions had no cracking, meaning that the use of top movement joints and/or reinforced coatings can be beneficial to prevent partition damaging from the deflection of concrete structures.

Therefore, establishing the relationship between the results obtained in the simulations, a broader long term relative deflections limits for structures (d/L creep) can be established to prevent damaging traditional partitions used in residential buildings in Portugal, considering the span of slabs and partition up to 6m, Tab5.

Table 5. Suggested long term relative vertical deflection limits (d/L creep) for concrete slabs/beams to avoid damage in traditional clay partitions walls in Portugal.

Type of partition	Vertical deflection / span (d/L creep)	
	Partitions with lateral movement/detachment joints and top/base bonding joints	Partitions with top movement/detachment joints and lateral/base bonding joints
Unreinforced masonry .UMW	< 1/1700	< 1/1200
Masonry wall with RMW-GFM1coating	< 1/1300	< 1/1000
Masonry wall with RMW-GFM2 coatings	< 1/1000	< 1/700

In conclusion, the proposed two step numerical method, that included calibration through some experimental results obtained from lab tests performed on relatively small samples, has the potential to obtain a more realistic simulation of larger partition walls loaded by the vertical deflections of concrete structures, and to obtain a more accurate estimation of structural deflections limits to avoid damage in partition walls. The application of this calibrated numerical method to a case study of traditional masonry partitions used in Portugal highlighted a high risk of damage when these walls are loaded by the structural deflection limits recommended in technical literature (1/1000 to 1/500), especially when no wall/structure detachment/movement joints or no reinforcement techniques are used. Therefore, based on the results obtained is this study some structural deflections limits were suggested to avoid damage in these partitions when using top or lateral movement joints and reinforced coatings with GFM.

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