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Application of Mechanics of Structure Genome in the homogenization of masonry reinforced by CFRP

Willian Tcheldon Oliveira Santos[1], Alícia Caroline de Lima Silva[1], Gabriela Silveira de Azevedo[1], Francisco Patrick Araujo Almeida[2]

[1]*Tecnology Center, Federal University of Alagoas*
Lourival Melo Mota Ave, n/n, Tabuleiro do Martins, Maceió, 57072-970, Alagoas, Brazil
tcheldon.ufal@gmail.com, alicia.lima@ctec.ufal.br, gabriela.azevedo@ctec.ufal.br
[2]*Laboratory of Scientific Computing and Visualization, Tecnology Center, Federal University of Alagoas*
Lourival Melo Mota Ave, n/n, Tabuleiro do Martins, Maceió, 57072-970, Alagoas, Brazil
patrick@lccv.ufal.br

Abstract. Masonry is one of the most widely used construction methods worldwide, however, as it is a heterogeneous material, its modeling is presented as a time-consuming process. As one of the main difficulties about working with a composite material is due to its anisotropy, caused by the different physical properties of each present component, mathematical or computational techniques for structural analysis have become essential tools in this study. In this article, the used technique is Mechanics of Structure Genome (MSG), because it allows the obtainment of three-dimensional models from simpler systems and smaller dimensions. The tests were performed in the computational tool SwiftComp, available for computers and also in its mobile version minimizing computational costs and enabling the homogenization of the studied composite, which is masonry reinforced by mesh of carbon fiber reinforced polymer (CFRP). After possessing the Young's modulus and the Poisson's ratio of the components, both of the CFRP and of the masonry, it is possible to perform the homogenization of each one, separately. Thus, the elastic constants of each of them are obtained to finally present the three-dimensional elastic properties of the masonry reinforced by CFRP, assuming a small variation for the Poisson's ratio of the matrix, in order to obtain the constitutive relation of the element.

Keywords: Mechanics of Structure Genome, Masonry, Homogenization, CFRP, Elastic Properties

1 Introduction

Even though masonry is one of the oldest construction methods it still is one of the most widely used in the industry. Despite that, since it is an anisotropic material generally formed by blocks and a thin layer of mortar, it presents a heterogeneous character and a non-linear constitutive behavior from its elements, according to Cecchi et al. [1]. Therefore, the process of modeling it is considered to be difficult, which explains why studies focusing on its structural properties are lacking, specially if any type of reinforcement is added to the structure.

As Creazza et al. [2] states, Fiber Reinforced Polymers (FRP) are composites that can be successfully used to reinforce masonry walls of new buildings and existing ones, playing an important role in the restoration and strengthening of historic and endangered buildings, due to its advantages as an external intervention that respects the original construction. Regardless of the higher costs, when compared to traditional materials, it is more advantageous.

In this case, besides the general elements of masonry, the third material of the structure studied is mesh of Carbon Fiber Reinforced Polymer (CFRP), analysed in two different situations, symmetrical and asymmetrical layups, for further comparison.

This paper proposes to perform the homogenization of masonry reinforced by CFRP carried out through a semi-analytical technique called Mechanics of Structure Genome (MSG) which consists primarily in a low-cost method of multiscale analysis implemented into a computer code called SwiftComp. This code is executable in computers and also in smartphones, available for iOS and Android operating systems, the latter was released recently, making the procedure of homogenization more accessible. However, the mobile version presents limitations when compared to the computer one.

2 Mechanics of Structure Genome

Mechanics of Structure Genome (MSG) is a multiscale constitutive modeling technique developed by Yu [3] that can be applied to all types of composite structures whether they are beams, plates/shells or even three-dimensional (3D). MSG was proven by Almeida and Lourenço [4, 5] to be just as accurate as other techniques of homogenization such as the Finite Element Method (FEM), including when it comes to masonry homogenization, but a lot less complicated, with no need of any boundary conditions by the final user.

The objective of this method is to use a small mathematical portion, named Structure Gene (SG), containing the necessary constitutive information for the characterization of an element, so that this way, after the homogenization process, they can replace the original heterogeneous material, making possible that the analysis of the desired structure is performed in a simplified way without losing its particularities, as in the representation of Fig. 1.

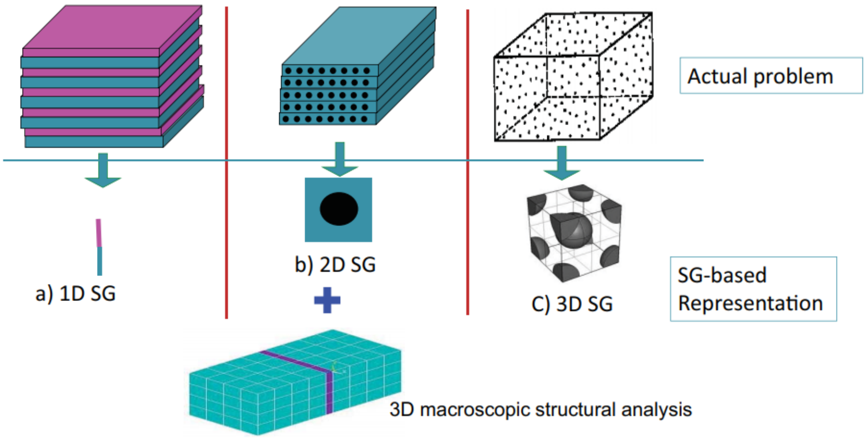


Figure 1. SG for 3D structure, Yu [6]

In addition to performing homogenization, the method can also calculate the local behavior through the dehomogenization process based on the global behavior of the structure, but in this study, this was not treated.

2.1 Homogenization of CFRP from a 2D SG

To initiate the procedure, the CFRP was defined as an element formed by fiber and matrix. Despite having some restrictions when compared to the computer version, the mobile version can also perform this homogenization (fiber + epoxy resin), as it is a two-dimensional model. The mechanical properties of the reinforcement are presented in Table 1.

Table 1. CFRP laminate mechanical properties, Cecchi et al. [1]

	Fiber	Matrix 3.0 - Epoxy PRM
E: Young's modulus (GPa)	230	3.14
V: Volumetric fraction (%)	33.3	66.6

Although the material of the matrix, along with its Poisson's ratio (ν), were not specified by Cecchi et al. [1, 7], it is possible to assume, taking its Young's modulus as the reference, 3.14 GPa, that it stands between a polyester (E = 2.8 GPa e $\nu = 0.30$) and a polyimide (E = 3.5 GPa e $\nu = 0.35$). Therefore, aiming the verification of the behavior of the mechanical characteristics of CFRP, in the homogenizations different values were considered for the Poisson's ratio, ranging from 0.30 to 0.35, with intervals of 0.01. For the fiber, carbon (IM), it was considered a Poisson's ratio of 0.20.

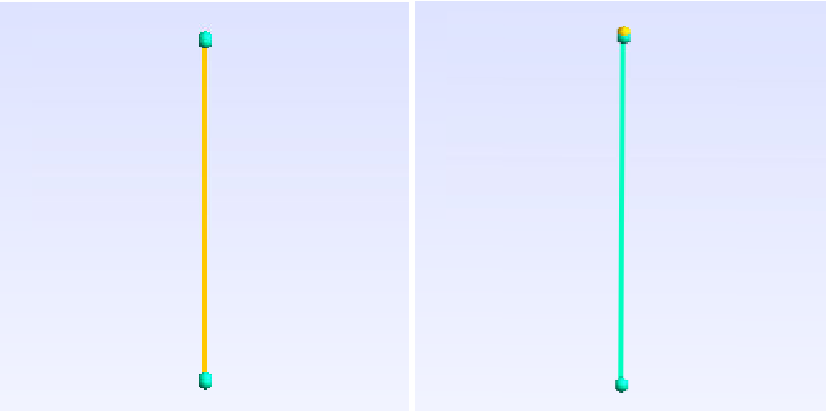
2.2 Homogenization of masonry reinforced by CFRP from a 1D SG

From the obtained Engineering Moduli, it became possible to accomplish the main analysis through a new homogenization process, between the masonry, coefficients presented by Almeida and Lourenço [4], and the CFRP, in order to obtain coefficients that relate to the reinforced structure, and it is also possible to carry out a comparative analysis for the performances of the different types of reinforcements considered previously.

This time, the homogenization process was carried out for 1D SG, in order to work with a tridimensional structure. Furthermore, in order to meet the coordinate reference used by SwiftComp, in addition to ensuring equivalence between the coefficients presented by both materials, it was necessary to rotate the coordinates of masonry. Consequently, for the results obtained (Tables 2, 3, 4 and 5) we will treat axis 1 as the vertical direction, axis 2 as the horizontal direction and axis 3, orthogonal to the masonry plane.

For the purposes of this study, the blocks are assumed to be the known UNI 5628/65, a brick with the following dimensions: 250 mm x 120 mm x 55 mm, and the thickness of the mesh of CFRP is 1 mm. The blocks have Young's modulus of 11,000 MPa and Poisson's ratio of 0.20. For the mortar, a thickness of 10 mm, a Young's modulus of 2,200 MPa and a Poisson's ratio of 0.25 were considered.

Two different methods were also proposed for the reinforcement, which was modeled as a continuous orthotropic layer, in order to consider the different peculiarities of the structures to be worked and aiming to analyse not only the visually perceptible advantages, but mainly the difference between the performance of each one. In the first one, the reinforcement is carried out in a symmetrical format, in order to obtain CFRP mesh placed on both sides of the masonry showed in Fig. 2(a). In the second, the reinforcement plate is placed only on one side of the masonry, as in Fig. 2(b), which ends up being an advantage in the case of application in historical patrimony, which must remain with its outer surface untouched. In the method used the hypothesis of perfect continuity between the layers according to Cecchi et al. [7].



(a) Symmetric SG 1D

(b) Asymmetric SG 1D

Figure 2. SG 1D: Masonry reinforced by CFRP

3 Numerical Results

The outcome of the homogenization of CFRP was the obtainment of the Engineering Modulus. In order to analyse the impact of the Poisson's ratio throughout the results, the percentage difference between the elastic constants considering the Poisson's ratio of the matrix as 0.30 and 0.35 was calculated and is displayed in Table 2.

From now on, the Young's Moduli (E) and Shear Moduli (G) are presented in MPa.

When compared to the other constants, E1 has a higher order of magnitude, since it is the longitudinal direction of the fibers, therefore, the more resistant one. In the comparison of the results of $\nu = 0.30$ and $\nu = 0.35$, it is possible to notice that for $\nu 23$, for example, the difference comes as an increase of 25.03%, which implies that the variation of the Poisson's ratio has to be carried out through the second homogenization.

The results of the following homogenization are presented in Table 3, for the asymmetric reinforced masonry and in Table 4, for the symmetric one.

Table 2. Results of the homogenizations and the difference for 0.30 and 0.35 Poisson's ratio (ν) in %

	$\nu = 0.30$	$\nu = 0.31$	$\nu = 0.32$	$\nu = 0.33$	$\nu = 0.34$	$\nu = 0.35$	%
E1	78690.130	78692.112	78694.279	78696.632	78699.169	78701.892	0.01
E2/E3	6560.178	6640.088	6726.949	6821.458	6924.418	7036.762	7.26
G12/G13	2375.7483	2357.9462	2340.4091	2323.1308	2306.1059	2289.3287	-3.64
G23	1937.3154	1925.1357	1913.2400	1901.6290	1890.3047	1879.2699	-3.00
$\nu12/\nu13$	0.25896608	0.26524548	0.27159956	0.27802970	0.28453729	0.29112380	12.42
$\nu23$	0.33978451	0.35527838	0.37146811	0.38841183	0.40675380	0.42483370	25.03

Table 3. Properties of masonry reinforced by CFRP in an asymmetrical layup

	$\nu = 0.30$	$\nu = 0.31$	$\nu = 0.32$	$\nu = 0.33$	$\nu = 0.34$	$\nu = 0.35$	%
E1	7594.236	7594.325	7594.424	7594.532	7594.650	7594.780	0.01
E2	8683.661	8684.155	8684.698	8685.294	8685.951	8686.674	0.03
E3	9349.939	9351.545	9353.275	9355.131	9357.146	9359.247	0.10
G12	2615.0015	2614.8544	2614.7095	2614.5667	2614.4260	2614.2873	-0.03
G13	2717.8085	2717.6145	2717.4205	2717.2266	2717.0327	2716.8388	-0.04
G23	3571.9389	3571.5945	3571.2541	3570.9177	3570.5858	3570.2585	-0.05
$\nu12$	0.16568617	0.16573194	0.16577983	0.16583007	0.16588292	0.16593868	0.15
$\nu13$	0.15817724	0.15824984	0.15832510	0.15840320	0.15848490	0.15856869	0.25
$\nu23$	0.19282692	0.19292773	0.19303325	0.19314385	0.19326456	0.19338221	0.29

Table 4. Properties of masonry reinforced by CFRP in a symmetrical layup

	$\nu = 0.30$	$\nu = 0.31$	$\nu = 0.32$	$\nu = 0.33$	$\nu = 0.34$	$\nu = 0.35$	%
E1	8177.457	8177.633	8177.827	8178.040	8178.274	8178.530	0.01
E2	8683.126	8684.130	8685.232	8686.443	8687.774	8689.239	0.07
E3	9336.318	9339.529	9342.979	9346.681	9350.700	9354.892	0.20
G12	2613.0404	2612.7486	2612.4611	2612.1778	2611.8988	2611.6237	-0.05
G13	2714.6048	2714.2209	2713.8372	2713.4536	2713.0701	2712.6866	-0.07
G23	3547.4049	3546.7313	3546.0654	3545.4076	3544.7586	3544.1188	-0.09
$\nu12$	0.16625002	0.16634092	0.16643601	0.16653574	0.16664062	0.16675125	0.30
$\nu13$	0.15913870	0.15928243	0.15943142	0.15958600	0.15974766	0.15991343	0.49
$\nu23$	0.19610442	0.19630844	0.19652193	0.19674569	0.19698971	0.19722780	0.57

Even tough the first homogenization implied that the Poisson's ratio variation needed to be considered, the homogenization of the masonry and the CFRP showed the opposite, similar results were obtained for different Poisson's ratio. This can be seen in Table 3, as well as in Table 4, since the column that displays the percentage difference shows that there is only a small variation on the outcomes.

So, to compare the performance of the two types of reinforcement, the results of the homogenization performed using 0.35 as Poisson's ratio were chosen for the analysis, seen in Table 5.

Table 5. Comparison of the properties of unreinforced masonry (URM) and reinforced masonry (RM), for $\nu = 0.35$

	URM	Asymmetric RM	Gain (%)	Symmetric RM	Gain (%)
E1	7001.289	7594.780	8.48	8178.530	16.81
E2	8681.084	8686.674	0.06	8689.239	0.09
E3	9360.803	9359.247	-0.02	9354.892	-0.06
G12	2616.9953	2614.2873	-0.10	2611.6237	-0.21
G13	2721.0733	2716.8388	-0.16	2712.6866	-0.31
G23	3597.2321	3570.2585	-0.75	3544.1188	-1.48
$\nu12$	0.16511541	0.16593868	0.50	0.16675125	0.99
$\nu13$	0.15719808	0.15856869	0.87	0.15991343	1.73
$\nu23$	0.18911121	0.19338221	2.26	0.19722780	4.29

According to Table 5, it is noticeable that the major increase of the elastic constants was on the axis of E1, that represents the vertical direction of the masonry, which was already expected. In contrast, there are decreases in E3, G12, G13 and G23, but when compared to the increase in the E1 axis, the loss is considered very low (between 0.06 and 1.48%). As a result, the reinforcement acts as an important element since it enables the growth of 8.48% for asymmetric RM, and 16.81% for the symmetric RM. In fact, the gain (%) for the symmetric RM, for most of the elastic constants, is almost the double of the asymmetric, that is an important outcome to analyse which type of reinforcement is more adequate, depending on the situation.

4 Conclusions

The results presented in this paper show that MSG is a method of multiscale analysis that can easily perform different types of homogenization and can be successfully used in the study of masonry reinforced by CFRP. Furthermore, it is possible to understand that CFRP is an impressive reinforcement, given it strengthens masonry significantly and acts externally, preserving the original structures.

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