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THE EARTHQUAKE BEHAVIOUR OF LOW-RISE HOUSES MADE BY EITHER REINFORCED CONCRETE, PARTIALLY REINFORCED MASONRY OR A NOVEL STEEL COMPOSITE SYSTEM

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Abstract. *This paper discusses features for the seismic design of low-rise houses made by three different construction techniques. A typical two-storey residential house with a basement is chosen for examination. This house, with the same dimensions in elevation and plan, is being built by three different construction techniques, thus resulting in three different structures. The first is that of conventional reinforced concrete construction whereas the second is that of partially reinforced masonry. The 2nd construction technique utilizes such hollow ceramic bricks that longitudinal as well as transverse reinforcement can be accommodated within the vertical walls built with these bricks. The compression, flexural and shear behaviour of such masonry walls has been documented by a series of experiments conducted for this purpose. The novel 3rd construction technique utilizes steel structural elements in the form of sheets for the slabs or cold-formed sections for the beams and columns in order to form the structure, together with a special light weight concrete mix (SLWC). The mechanical properties of the SLWC mix were found from a series of laboratory tests. This investigation is mainly numerical, making use at the same time of the mechanical properties of the materials utilized in each one of the three different construction techniques as determined through laboratory testing, especially those of the innovative Super Light Weight Concrete. The seismic design follows the provisions of the Greek seismic code or those of the Euro-Codes; it utilizes the dynamic spectral method that is incorporated in the commercial software SAP2000. The main dynamic response characteristics are first established and discussed for each one of the three different structures made by the three distinct construction techniques mentioned before. Next, the demands to be used in the earthquake design at critical sections of the various structural elements are also computed and compared with the design strengths as provided by the relevant codes. Use is made here of strength data documented during the laboratory tests. The maximum design quantities for the same two-storey structure built by the three different techniques, in terms of storey drifts, and base shear as well as in terms of slab deflections are compared and discussed.*

1 INTRODUCTION

Seismic design demands that a structure should sustain its main functions, such as its safety and serviceability, both during and after a particular earthquake exposure. A structure is considered safe if it does not endanger the lives and well-being of the occupants, by partially or completely collapsing. In general, the greater the dead load masses, the larger the seismic forces imposed on the structure. Consequently, it is desirable to possibly decrease the seismic forces through a decrease of the dead load mass for a structure. It is also desirable that this decrease in seismic loads and seismic demands on the structural members of a building may also lead to a decrease in the final construction cost.

Lightweight concrete can be defined as a type of concrete mix which includes an expanding agent which increases the volume of the mixture and decreases the dead weight while giving additional qualities such as nailibility and thermal insulation. It is lighter than the conventional concrete with its dry density ranging form 250 kg/m^3 to 1840 kg/m^3; that is 90% to 26% lighter than regular conventional concrete mixes. It was first introduced by the Romans in the second century when 'The Pantheon' was constructed using pumice, the most common type of aggregate used in that particular year [1]. From there on, the use of lightweight concrete spread widely across other countries such as the USA, the United Kingdom and Sweden. The main specialities of lightweight concrete are its low density and thermal conductivity. Its advantages are that there is a reduction of dead load, faster building rates in construction and lower haulage and handling costs.

The present study investigates features of a low-rise house incorporating, in its construction, light weight concrete together with steel structural elements in the form of sheets for the slabs or cold-formed sections for the beams and columns. The purpose of the current numerical investigation is to focus on the consequences of such an innovative construction on the dynamic response and earthquake design of low-rise houses made by such an innovative construction as compared with two other well established conventional constructions; that is conventional reinforced concrete construction or partially reinforced masonry. The properties of special light concrete mix, to be incorporated with the novel construction technique, have been documented by a series of experiments conducted for this purpose at the Laboratory of Strength of Materials and Structures of Aristotle University.

2 EXPERIMENTAL INVESTIGATION OF NOVEL LIGHT WEIGHT CONCRETE

A series of compressive and flexural tests were conducted at the Laboratory of Strength of Materials and Structures of Aristotle University in order to determine the mechanical properties of the innovative Super Light Weight Concrete (SLWC) that was intended for use in the numerically investigated building of the 3rd construction type. In total two materials were investigated; the first with density 350 kg/m^3 and the second with density 800 kg/m^3. The obtained results are listed in Table 1. SLWC with density 350 kg/m^3 has an average maximum compressive strength equal to 1,94Mpa and tensile strength (defined from four point bending tests) equal to 0,53 MPa. SLWC with density 800 kg/m^3 has an average maximum compressive strength equal to 2,54MPa and tensile strength (defined from four point bending tests) equal to 0,83 MPa. In the framework of present numerical investigation, the mechanical properties of the SLWC mix with density 800 kg/m^3 are considered for the simulation of the building made with the 3rd construction type.

Figure 1 depicts the average overall stress-strain behaviour of both 350kg/m^3 and 800kg/m^3 SLWC. Both types of SLWC are relatively soft with a modulus of elasticity equal to 150MPa. Both materials can keep their 80% strength for big deformations, especially the SLWC with density 350kg/m^3.

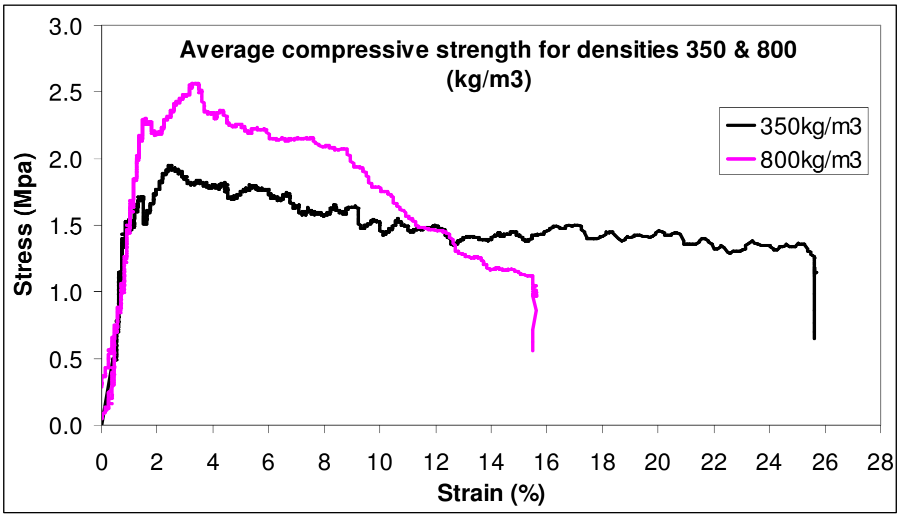


Figure 1. Average compressive strengths for SLWC 350 & 800 (kg/m^3)

test	Max tensile stress from flexural tests (N/mm^2)		Max compressive stress (N/mm^2)					
			350 kg/m^3			800 kg/m^3		
	350 kg/m^3	800 kg/m^3	max	@ strain 2%	@ strain 10%	max	@ strain 2%	@ strain 10%
1st	0,52	0,89	1,95	1,77	1,83	2,51	2,3	1,75
2nd	0,52	0,8	1,95	1,66	1,48	2,57	1,5	1,48
3rd	0,56	0,81	1,93	1,63	1,33	2,55	2,1	1,6
Average	**0,53**	**0,83**	**1,94**	1,69	1,55	**2,54**	1,97	1,61

Table 1. Tensile and compressive max stresses for SLWC 350 & 800 (kg/m^3)

3 EXPERIMENTAL INVESTIGATION OF PARTIALLY REINFORCED MASONRY

The properties of partially reinforced masonry construction, utilized in the framework of the present numerical study, were found from an extensive laboratory investigation with a considerable number of partially reinforced masonry piers. All these masonry specimens were constructed with the special "Greek" brick with vertical holes depicted in figure 2. These brick units were produced in three different types, that is A, B and C. Brick D, was the unit that was industrially produced in large quantities and was used for the majority of the specimens. The measured strength of the brick unit is given in Table 2. The partially reinforced pier specimens were subjected to horizontal cyclic seismic-type loading together with the simultaneous application of vertical load at the top (figure 3), thus simulating prototype conditions. Detailed information of this experimental sequence and the obtained results is given in [7], [8], [9], [10]. These partially reinforced piers were of the following geometry:

- Length 1330mm, height 1330mm and thickness 154mm.
- Length 660mm, height 1330mm and thickness 154mm.

Apart from the above geometry, which must be considered as ½ scaled specimens and represent the bulk of the testing sequence, a limited number of specimens near to prototype scale were also tested. These specimens were of the following geometry:

- Length 2700mm, height 2475mm and thickness 320mm.
- Length 2700mm, height 2475mm and thickness 154mm.

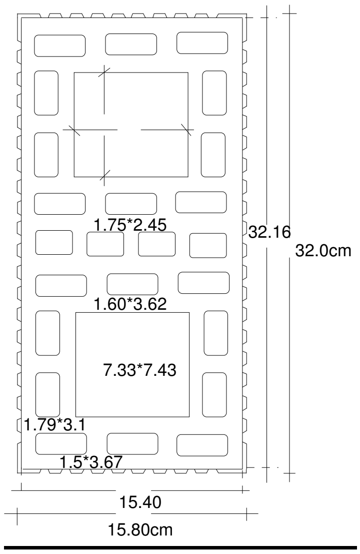


Figure 2. special "Greek" brick with vertical holes

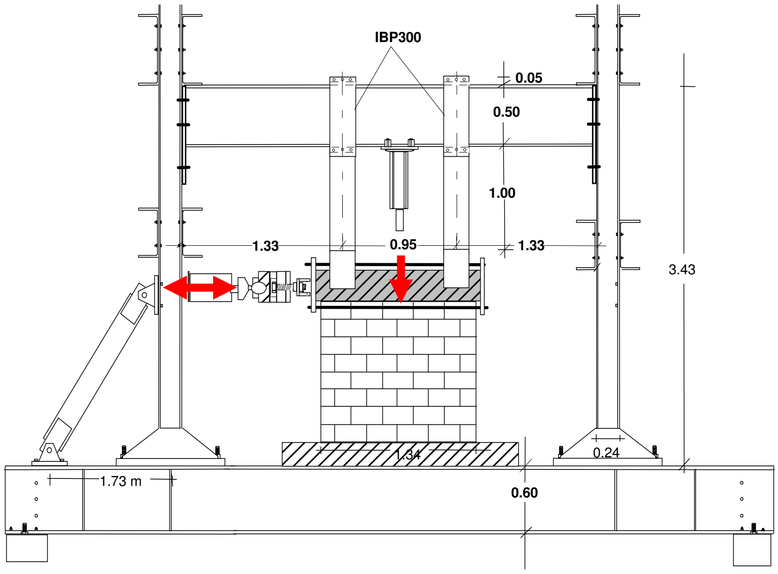


Figure 3. Partially reinforced masonry piers simultaneously loaded with a horizontal cyclic seismic-type load as well as with a vertical load

Brick Unit	Strength (Gross) fb (MPa)	Strength (Net) fb (MPa)	% of Voids
B	2.59	5.20	50%
C	8.93	17.38	49%
D	7.14	15.48	54%

Table 2. Compressive Strength of Brick Units

The average compressive strength of the mortar employed in the construction of these piers was either 2.1MPa for the relative weak mortar or 4.27MPa for the relatively strong mortar. Various longitudinal and transverse reinforcing arrangements were examined together with a variation of the level of uniform compression.

4 NUMERICAL SIMULATION OF TWO-STOREY STRUCTURE WITH BASEMENT

The present study investigates the static and dynamic response of a typical two storey building with a basement [5], [6]. The typical floor plan of the building is illustrated in figure 4. The overall dimensions of the building in plan are 13,40m x 12,70m.

Three such buildings with the same dimensions but made with three different construction techniques are studied. The maximum seismic response of these three buildings is obtained numerically and comparison is made. The seismic loading is defined following the provisions of the current Greek Seismic Code [4]. This numerical dynamic and earthquake loading study was made by discretizing each building with finite elements (FE) and then utilizing the capabilities of the commercial software SAP2000 based on elastic analysis assumptions.

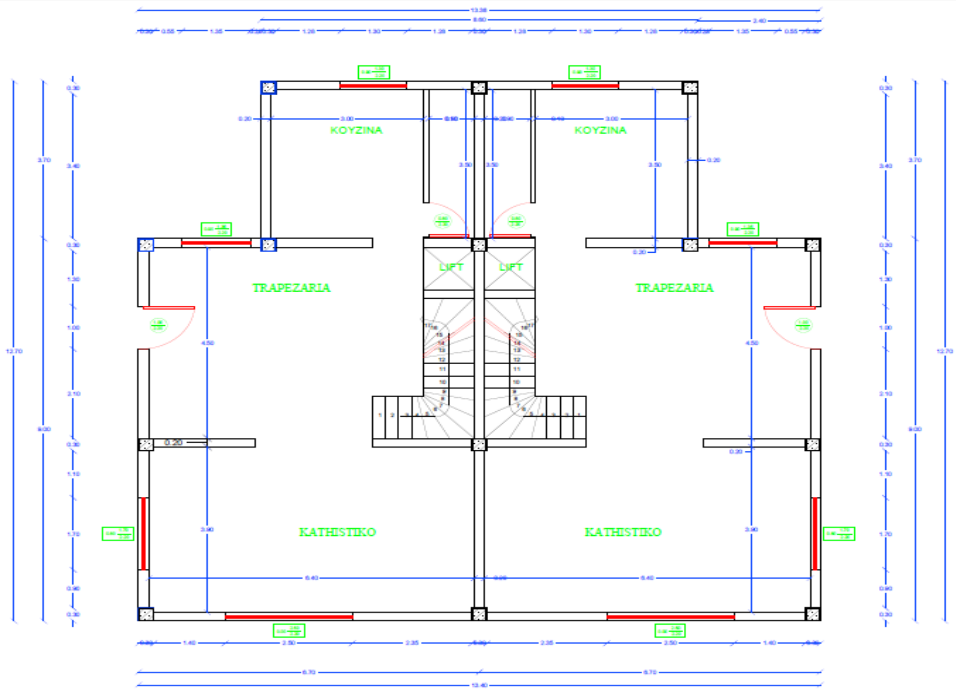


Figure 4. Typical floor plan of low-rise building (3-storey)

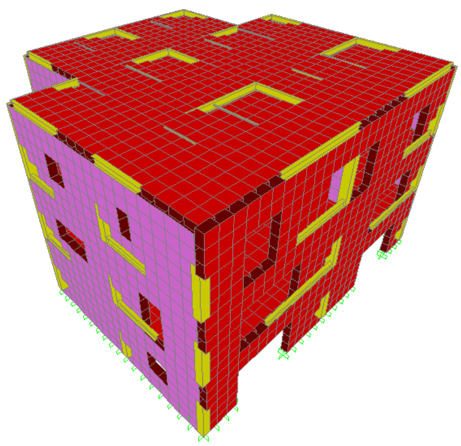


Figure 5a. F.E. Discretization a) used for the numerical simulation of the behaviour of the house built by either partially reinforced masonry (PRM) or Composite Innovatiove Technique (CIT)

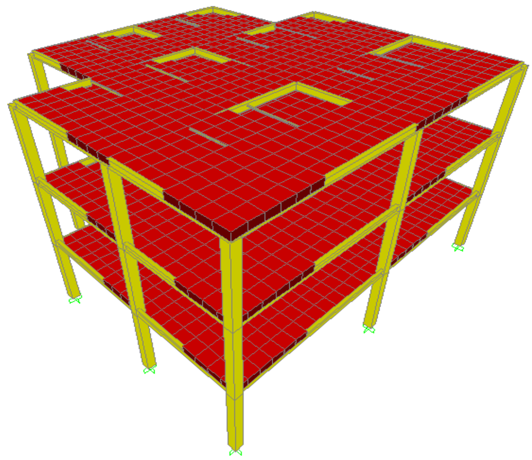


Figure 5b. F.E. Discretization b) used for the numerical simulation of the behaviour of the house built by reinforced concrete (R/C)

The considered three different construction types are:

i) Reinforced Concrete (R/C) [3]

ii) Partially Reinforced Masonry (PR/M)

iii) Composite Innovative Technique (CIT) combining SLWC (800kg/m^3) with cold formed thin-walled steel.

Figures 5a and 5b depict the employed discretizations as utilized, combined with each one of the three construction techniques mentioned before. The discretization depicted in figures

5a and 5b combined with the assumptions made according to the mass and stiffness properties of the constituent materials employed in each construction technique, resulted in a large number of numerical models. The following 4 models will be considered in the results presented in this paper:

Model CIT-II, representing the house built with the Composite Innovative Technique (CIT) combining SLWC (800kg/m^3), assuming a stiffness of SLWC equal to 500MPa for the infilled walls within the steel frames made by SLWC, employing discretization a (figure 5a)

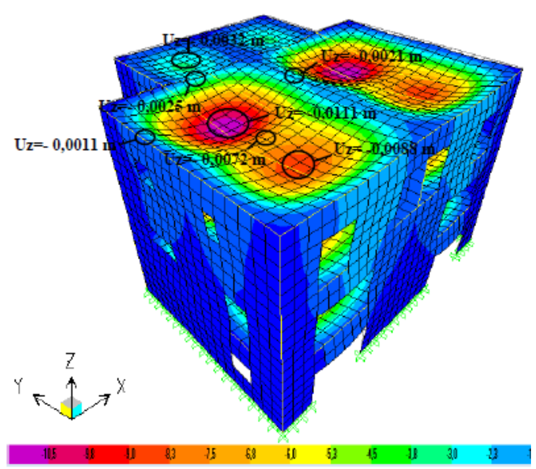
Model CIT-IV, representing the house built with the Composite Innovative Technique (CIT) combining SLWC (800kg/m^3), assuming zero stiffness of SLWC for the infilled walls within the steel frames made by SLWC, employing discretization a (figure 5b).

Model R/C, representing the house built with the Reinforced Concrete (R/C), employing discretization b (figure 5b)

Model PR/M, representing the house built with the Partially Reinforced Masonry (PR/M), employing discretization b (figure 3), employing discretization a (figure 5a).

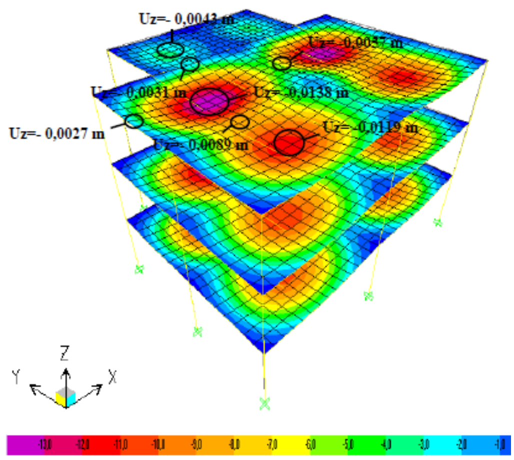
5 PERFORMANCE OF THE SLABS UNDER GRAVITATIONAL FORCES

Figures 4a and 4b depict the deflections of the slab at the top of the 2nd storey as resulting from the load combination *1,35(G1+G2) +1,5Q* whereby: G1 the dead loads, G2 additional dead loads and Q live loads. Figure 4a corresponds to the deflection patterns for *Model CIT-II* whereas figure 4b for *Model CIT-IV.*



1,35(G1+G2) +1,5Q , Model CIT-II

Figure 6a. Deflections of the slab at the top of the 2nd storey



1,35(G1+G2) +1,5Q , Model CIT-IV

Figure 6b. Deflections of the slab at the top of the 2nd storey

Name of Storey Slab	*Model CIT-II,* ***1,35(G1+G2) +1,5Q*** Slab Max. deflections Uz (mm)	*Model CIT-IV,* ***1,35(G1+G2) +1,5Q*** Slab Max. deflections Uz (mm)
Bottom of 1st storey	9.4	12.8
Top of 1st storey	9.8	12.8
Top of 2nd storey	11.1	13.8

Table 3. Slab maximum deflection values

The maximum slab deflection values predicted from these two numerical models for the slabs at all three levels are listed in Table 3. These values correspond to the two examined models, *Model CIT-II and Model CIT-IV,* and for the load combination *1,35(G1+G2) +1,5Q* (figures 6a and 6b)**.**

In order to check whether the slabs constructed in the proposed composite way, that is the utilization of corrugated thin metal steel sheets and the SLWC concrete mix, comply with the criteria of functionality the maximum deflections were also obtained for numerical models *Model CIT-II* and *Model CIT-IV* for the load combination*(G1+G2) +Q*. This load combination is designates as SIS. The inequality (1) describes the limit ($_{max}\boldsymbol{\delta}^{1all}$) for the maximum deflection of each slab loaded with the load combination SIS ($_{max}\boldsymbol{\delta}^{SIS}$). This maximum allowable deflection $_{max}\boldsymbol{\delta}^{1all}$ for this load combination is set equal to L_{max} / 250. L_{max} the maximum span for the slab that is checked.

$$_{max}\boldsymbol{\delta}^{1all} > {}_{max}\boldsymbol{\delta}^{SIS} \quad (1)$$

An additional limit was also used for ensuring the functionality of these slabs. This time the maximum deflection of the slab produced by the live loads Q ($_{max}\boldsymbol{\delta}^{Q}$) must be less than $_{max}\boldsymbol{\delta}^{2all}$, (inequality (2). This maximum allowable deflection ($_{max}\boldsymbol{\delta}^{2all}$) is set equal to L_{max} / 350. L_{max} the maximum span for the slab that is checked. This limit value is set for partitions that should have an extra degree of protection otherwise the limit for $_{max}\boldsymbol{\delta}^{2all}$ is set to a less stringent value equal to L_{max} / 300.

$$_{max}\boldsymbol{\delta}^{2all} > {}_{max}\boldsymbol{\delta}^{Q} \quad (2)$$

The maximum deflection values obtained from the numerical simulation models *Model CIT-II* and *Model CIT-IV,* representing the structures to be built with slabs with the proposed innovative construction technique, i.e. utilizing corrugated thin metal steel sheets and the novel SLWC concrete mix, comply with the criteria of functionality of their maximum deflections, as described with inequalities (1) and (2) above. These criteria are also satisfied for the reinforced concrete slabs incorporated in *Model R/C* and *Model PR/M.*

6 MODAL ANALYSIS

Table 4 lists the results of the modal analysis in terms of eigen-period values together with the modal mass participation ratio values. This is done for the most significant translational eigen-modes x-x and y-y. Due to the distribution of the mass and stiffness the modal mass participation ratios for the main two translational x-x/y-y modes attains values larger than 66.5% of the total mass. Consequently, the sufficient accuracy can be attained by a dynamic spectral analysis that includes only the first 5 modes as they can mobilize modal masses larger that 85% to 90% of the total mass.

From the values of the eigen-periods for the 4 different models it can be seen that the dynamic system with the smallest eigen-period is *Model CIT-II.* This is due to the fact that this system has relatively less mass due to the presence of the SLWC as infilling material. In addition, the infilling material was given a stiffness equal to 500MPa. When this stiffness becomes equal to zero (*Model CIT-IV*) it results in a rather flexible dynamic system that has larger eigen-period values than the previous model (*Model CIT-II.*). The structure with partially reinforced masonry is stiffer and has larger mass than *Model CIT-II.*

	Eigen-mode	Eigen-Period (sec)	Modal Participation Ratio x-x	Modal Participation Ratio y-y
Model CIT-II	Translation x-x	0.193	0.780	-
	Translation y-y	0.138	-	0.808
Model CIT-IV	Translation y-y	0.370	-	0.830
	Translation[a] x-x	0.359	0.666	-
	Translation[b] x-x	0.275	0.175	-
Model R/C	Translation[a] x-x	0.370	0.083	-
	Translation[b] x-x	0.240	0.665	-
	Translation y-y	0.187	-	0.830
Model PR/M,	Translation[a] x-x	0.203	0.741	-
	Translation y-y	0.167	-	0.751
	Translation[b] x-x	0.071	0.087	-

Table 4. Eigen period and modal mass participation values for *Model CIT-II*

The resulting eigen-period values are somewhat larger than those of *Model CIT-II* and smaller than those of *Model CIT-IV*. The main translational x-x and y-y eigen-modes for model *Model CIT-II* are depicted in figures 7a and 7b, respectively, and for *Model CIT-IV* in figures 7c and 7d.

Model CIT-II

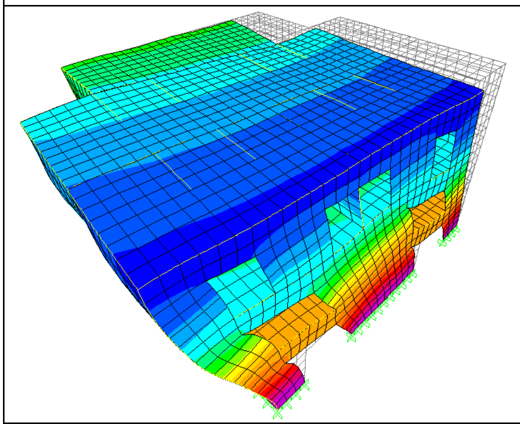


Figure 7a. Translation x-x, Eigen-Period 0.193 (sec) Modal Participation Ratio x-x 0.780

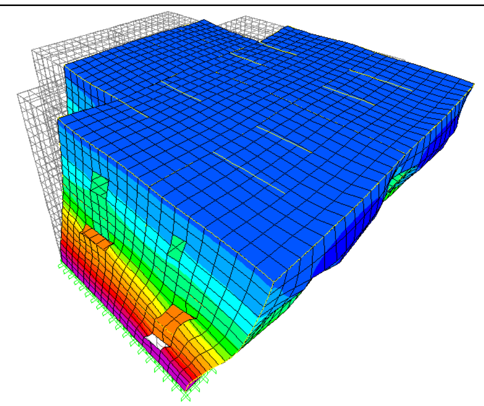


Figure 7b. Translation y-y, Eigen-Period 0.138 (sec) Modal Participation Ratio y-y 0.808

Model CIT-II

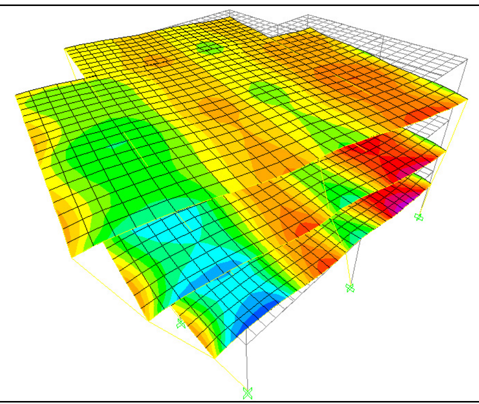


Figure 7c. Translation x-x, Eigen-Period 0.359 (sec) Modal Participation Ratio x-x 0.660

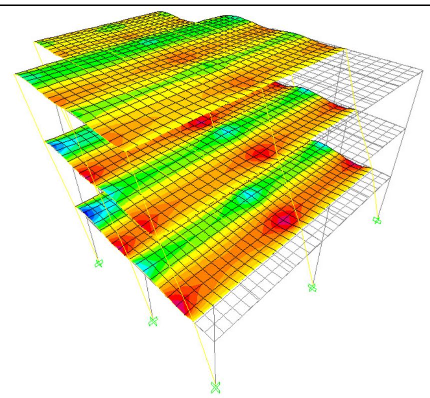
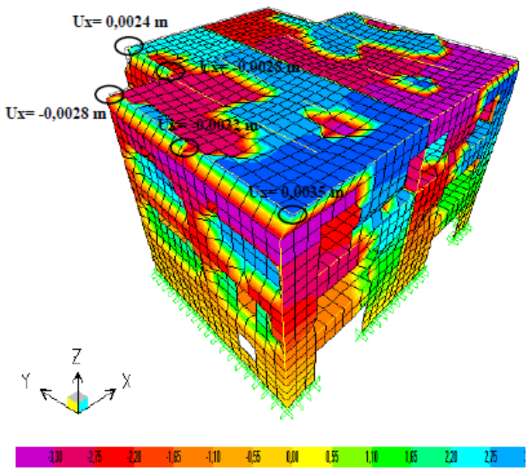


Figure 7d. Translation y-y, Eigen-Period 0.370 (sec) Modal Participation Ratio y-y 0.830

7 DYNAMIC SPECTRAL ANALYSIS

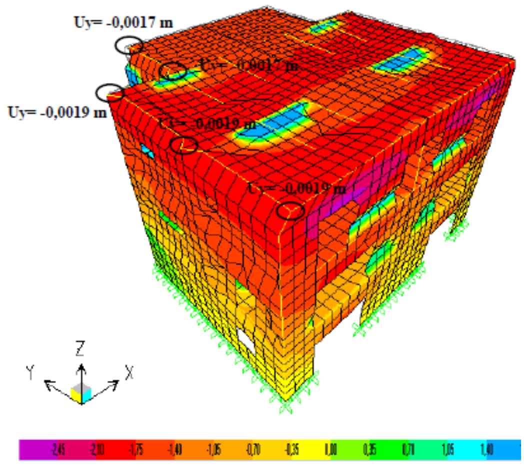
For all four models the dynamic response spectrum analyses were performed, taking into account the provisions of the Greek Seismic Code (EAK2000). As already explained in section 6, the dynamic spectral analysis could attain sufficient accuracy by including only the first 5 modes as they can mobilize modal masses larger that 85% to 90% of the total mass. The summation of the modal responses obtained from the dynamic spectral method are the results produced from the seismic loading designated as "*Seismic*" (either x-x, or y-y). Therefore the following loading combination was examined:

(G1+G2)+0,3Q + Seismic where: G1 the dead loads, G2 additional dead loads and Q live loads. (3)



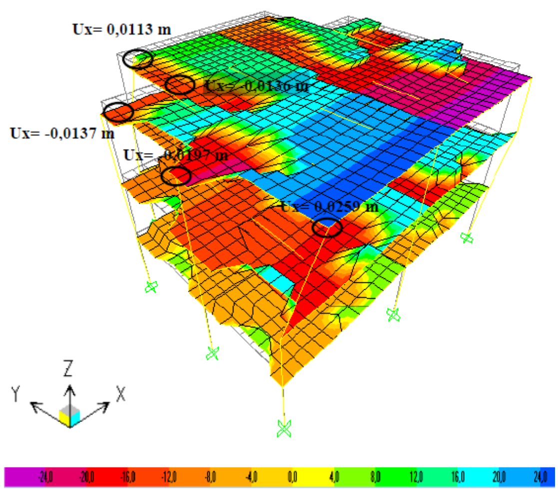
(G1+G2)+0,3Q + Seismic x-x

Figure 8a. Model CIT-II, Earthquake x-x, Maximum horizontal displacement Ux = 3.6mm at top 2nd storey slab



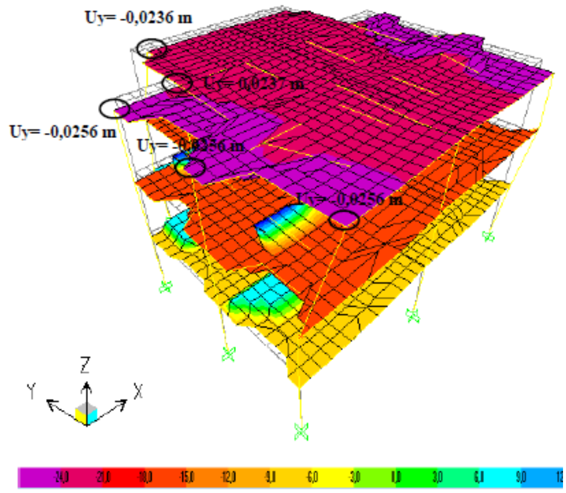
(G1+G2)+0,3Q + Seismic y-y

Figure 8b. Model CIT-II, Earthquake y-y, Maximum horizontal displacement Uy = 2.0mm at top 2nd storey slab



(G1+G2)+0,3Q + Seismic x-x

Figure 9a. Model CIT-IV, Earthquake x-x, Maximum horizontal displacement Ux = 26.0mm at top 2nd storey slab



(G1+G2)+0,3Q + Seismic y-y

Figure 9b. Model CIT-II, Earthquake y-y, Maximum horizontal displacement Uy = 25.6mm at top 2nd storey slab

Figures 8a and 8b display the horizontal displacement patterns for *Model CIT-II* and for load combination *(G1+G2)+0,3Q + Seismic*, in the direction x-x or y-y respectively. This is also depicted in figures 9a and 9b; however, this time for *Model CIT-IV* . Table 5 lists the Maximum horizontal displacement values at the three slab levels. As expected, when the SLWC panels contribute to the horizontal stiffness, as is the case for *Model CIT-II,* the horizontal displacements at the three slab levels are considerably smaller than for the case where such SLWC infill stiffness is ignored, as is the case for *Model CIT-IV.*

Name of Storey Slab	*Model CIT-II,* ***(G1+G2)+ + 0.3Q + Seismic*** Slab Max. Hor. Displacements Ux (mm) / Uy (mm)	*Model CIT-IV* ***(G1+G2)+ + 0.3Q + Seismic*** Slab Max. Hor. Displacements Ux (mm) / Uy (mm)
Bottom of 1st storey	1.4 / 0.8	7.5 / 7.3
Top of 1st storey	2.8 / 1.6	18.3 / 17.9
Top of 2nd storey	3.6 / 2.0	26.0 / 25.6

Table 5. Maximum horizontal displacement values at the three slab levels.

8 COMPARISON OF THE SEISMIC PERFORMANCE

Table 6 lists the base shear as obtained by the numerical solution of the dynamic spectral method utilizing the four models mentioned before. In the dynamic spectral method, the response modification factor was given the value of q=3.5 for *Model CIT-II, Model CIT-IV and Model R/C* and q=2.5 for *Model PR/M.* It is interesting to note that the models representing the proposed innovative construction technique resulted in significantly lower values for the base shear than either the conventional reinforced concrete construction or the construction utilizing partially reinforced masonry.

	Model CIT-II	*Model CIT-IV*	*Model R/C*	*Model PR/M*
Base Shear (KN)	608	608	1467	1720

Table 6. Base shear values as obtained by the four numerical model

In what follows two additional criteria will be employed. First, the maximum non-dimensional shear strain (γ) is obtained through equation (4) based on the maximum inter-storey drift value ($\Delta_{\varepsilon\lambda}$); where q is the response modification value and h is the storey height.

$$\gamma = \frac{q \cdot \Delta_{\varepsilon\lambda}}{2{,}50 \cdot h} \tag{4}$$

Next, a parameter (θ) is calculated, as an indicator of 2nd order effect, employing equation (5), ($N_{o\lambda}$) and ($V_{o\lambda}$) is the sum of the axial and shear forces per storey, respectively.

$$\theta = \frac{N_{o\lambda} \cdot q \cdot \Delta_{\varepsilon\lambda}}{V_{o\lambda} \cdot h} \tag{5}$$

Table 7 lists the maximum values for the parameters (γ) and (θ), as calculated from the numerical results obtained from the four numerical models, that is *Model CIT-II, Model CIT-IV, Model R/C, Model PR/M.* The maximum allowable values for these two parameters, that is γ^{max} and θ^{max} are also listed in this table. As can be seen, the house built with all four construction techniques are below the maximum allowable θ^{max} value, which indicates that they are not susceptible to 2nd order effects. This was expected for the conventional R/C or partially reinforced masonry construction techniques but it was less obvious for the proposed innovative construction technique, especially when the stiffening effect of the infill SLWC panels is not taken into account. Furthermore, the inter-storey maximum shear strain values are just above the maximum allowable value γ^{max} for *Model CIT IV* and *Model PR/M*. This should be further investigated for the infill SLWC panels. The relatively large γ value for the model representing the partially reinforced masonry construction is due to the large value of the base shear as well as to the relatively low value of Young's modulus assumed in the analysis for this type of construction (1300MPa).

Model	γ maximum value from numerical simulation	γ^{max} maximum allowable value	θ maximum value from numerical simulation	θ^{max} maximum allowable value
Model CIT II	0,00089	< 0,005	0,00853	< 0,10
Model CIT IV	0,00546	≈ 0,005	0,0053	< 0,10
Model R/C	0,00446	< 0,005	0,0043	< 0,10
Model PR/M	0,00602	≈ 0,005	0,058	< 0,10

Table 7. Maximum values of inter-storey shear strain (γ) values and 2nd order effect indicator

9 CONCLUSIONS

1. The dynamic and earthquake behaviour of a typical two-storey residential house with a basement is examined. This structure is built either using R/C or partially reinforced masonry. It is also studied when it is built using an innovative composite construction technique employing special light weight concrete mix and steel parts. The compression, flexural and shear behaviour of such special light weight concrete mix has been documented in a series of experiments conducted for this purpose at the Laboratory of Strength of Materials and Structures of Aristotle University. Similarly, the compression, flexural and shear behaviour of partially reinforced masonry piers was determined

2. From the values of the eigen-periods for the 4 different models it can be seen that the dynamic system with the smallest eigen-period is the model representing the innovative composite construction with an assumed stiffness of 500MPa for the infilling material. This is due to the fact that this system has relatively less mass due to the presence of the SLWC as infilling material. When this stiffness of the infilling material is assumed equal to zero (*Model CIT-IV*) it results in a rather flexible dynamic system with large eigen-period values. The structure with partially reinforced masonry is relatively stiff and has larger mass than *Model CIT-II.*

3. The models representing the proposed innovative construction technique resulted in significantly lower values for the base shear than either the conventional reinforced concrete construction or the construction utilizing partially reinforced masonry. This is mainly due to the low weight of the special SLWC concrete mix. It must also be noted that in the dynamic spectral method the response modification factor was given the value of q=3.5 for the

structures made with either reinforced concrete or with the innovative construction technique and the value of q=2.5 for the structure made by partially reinforced masonry.

4. The slabs of all three construction techniques conform with the functionality requirements. Moreover, all these houses are not susceptible to 2nd order effects.

5. The inter-storey maximum shear strain values are just above the maximum allowable value γ^{max} for the structure constructed with the innovative composite construction technique, assuming zero stiffness of the infilling material. This should be further investigated for the infill SLWC panels. The relatively large γ value for the model representing the partially reinforced masonry construction is due to the large value of the base shear as well as to the relatively low value of Young's modulus assumed in the analysis for this type of construction (1300MPa).

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