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The mantle of shotcrete as a method of intervention of masonry structures

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Abstract

The mantle of shotcrete (gunite) which is applied to one or both sides of masonry walls reinforces the masonry and influences the dynamic behaviour of the masonry as it changes the mass of the structure and increases the out-of-plane and the in-plane stiffness of the masonry walls. The research of this composite material's behaviour to both static and dynamic loading cases, is the subject of this work. Linear elastic mechanical behaviour of both masonry and gunite is considered throughout this paper. The finite element method is used. First the static and dynamic response based on the response spectrum analysis of two coupled walls, one of which being constructed by concrete and the other one by masonry, is examined. The detailed modelling allows us compare the contribution of the two materials in the overall behaviour of the composite structure. The same analysis is repeated for a reinforced masonry wall with gunite added on one side of it. Comparison of the results between the two analyses shows the change in eigenmodes and eigenfrequencies. These features are also of potential interest for inverse (quality inspection or damage identification) tasks. Moreover, the estimation of the stress level and the comparison with the maximum allowed tensile and compressive stresses permit us to understand the influence of gunite on masonry life. The effect of the gunite on the strengthening of masonry walls depends on the geometry of the walls, the remaining durability of the masonry and the loads. The whole methodology was applied to a small typical masonry structure as a case study.

1 Introduction

The intervention of masonry structures requires special knowledge and experience in order to select the appropriate method which leads to the required results. The effects on the dynamic behavior of the structure must be taken into account since the seismic excitation is considered to be the main cause of damage for civil engineer structures.

A mantle of shotcrete (gunite) is widely used for restoration and strengthening of masonry structures. This method influences both the strength and the dynamical characteristics of the structure. Although the effect of this intervention on the strength of the resulting composite structure is beneficial, this is not always the case for the dynamical characteristics of the structure. In fact, the addition of a layer made of gunite increases the stiffness and the mass of the masonry structure. The resulting changes of the eigenmodal characteristics may not be easily predicted for structures of complex geometrical shape and structural system. In turn, the gunite reinforcement may lead to a negative influence on the dynamical response of the structure, which depends on the eigenmodal characteristics of the structure and the dynamical excitation.

In this paper the effect of gunite on the dynamical characteristics and on the seismic structural response of a simple masonry wall is investigated by means of finite element modeling and of numerical experimentation.

2 Technology of gunite restoration

The idea of strength restoration using a mantle of shotcrete (gunite) is the addition of one or two layers of reinforced concrete on the one or both sides of an existing masonry wall. Thus a composite wall is producted. On the assumption that a perfect bonding between the two layers can be realized, the concrete layer, which is of higher stiffness, acts as reinforcement and carries a considerable amount of the external loading. This way the integrity, the strength and the bearing capacity of the resulting composite structure is enhanced.

In the case of big thickness of masonry structures or in the case of small structures (economic reasons), it can be used one-sided mantle (inner or external). Generally the construction of one-sided mantle inner is avoided because it causes serious problems to the functional of the building (like new electric's and hydraulics establishments, digging to the ground floor for the anchorage of the mantle between wooden floors or from concrete plates etc.) The thickness of one –sided mantle must be 10 cm nearly. The construction of the mantle is made step by step from down to up.

In reality the shotcrete is plastering, which is casted from distance on the repaired surface. Generally to the restorations the shotcrete of dry mix is preferable. The application of shotcrete does not need the formulation of the surface in order to avoid bending phenomena, which affect the usefulness of this method. The success of shotcrete is based on the ability of machine user who must have experience, perception and be skilful. The mechanical behavior of shotcrete depends on the physical properties of concrete, the reinforcement and the connection forces with the masonry. Due to the low percent of water and the minimum time of wet it has an increased connection force. The ability of fitness depends on the stone dimensions. In parallel if the exposed masonry surface has been throroughly cleaned by loose material, the shotcrete develops very high bond with the old masonry.[1] Additional shotcrete has greate resistance (strengthens) because of the strong condensation and the law percent of water. In opposite, it has higher possibility of cracking and for this reason the placement of steel netting is necessary which is suppoted to masonry wall on several places.

In Greece the gunite is widely used for restoration of old structures. From the technological point of view the application of this method does not require highly skilled personnel or equipment and in architectural restrictions and space limitations permit its applicability. It is usually the reinforcement method of choice. On the other hand, the facts that elements of large mass are added on the structure and that the initial structural system is changed are considered as serious drawbacks of this method. In this sense, smart intervention techniques (including strengthening using steel structural elements or prestressing) may be preferable.

3 Finite element modeling of the structure

The initial structure is modeled by three dimensional, solid finite elements. This is a general purpose, which allows for static and dynamic, linear and nonlinear analysis. If certain assumptions are met, one may consider using more economical, simplified one dimensional beam models, two dimensional plate or shell models or a combination of them. The gunite reinforcement is modeled by means of one or more layers of three-dimensional solid finite elements, which are perfectly connected to the existing structure. Analogously, for the simplified plate or shell models one uses multilayer composite elements.

One should mention here that the quality of the interconnection between the existing structure and the gunite layers might also be modeled in more details. Besides the rigid, perfectly bonded interface used in this study, semi-rigid linear or nonlinear elastic connections or even nonlinear joint elements may be used. The latter case includes interface elements or joint laws, which allow for the modeling of delamination effects and of the loss of the structural integrity between the initial structure and the reinforcing layer. In this paper the investigation is restricted to perfectly bonded interfaces and linear material laws.

Using the previously outlined finite element method static analysis is performed and the eigenmodal characteristics of the structure before and after the reinforcing intervention are calculated. Furthermore, for a given design spectrum, the dynamic response is calculated by using the modal analysis method. One should notice here that the design spectrum takes into account the characteristics of the expected dynamic (earthquake) loading, the significance of the structure, possible load magnification or change due to basement or soil characteristics etc. It is also worth mentioning that this method is required by the current aseismic design codes.

The effect of the gunite reinforcement on the dynamic response is studied here by means of the following methodology.[2] First, a certain design is assumed for the gunite layers. Then the previously described modal structural analysis is performed. It is obvious that the relation between the design variables (e.g., placement and thickness of gunite layers) and the response quantities is nonlinear and depends on the eigenmodal characteristics and the external loading in a complicated way. The generality of finite element method allows for the accurate calculation of this response. Comparisons of appropriately chosen results between the initial and the reinforced structure will demonstrate aspects of the studied effects. The whole design cycle may be used in a future work for the optimal design of the gunite reinforcement.

4 Numerical example

4.1 Modeling

As an example a simple wall of rectangular shape was considered with dimensions as shown in Figure 1a. For the gunite a second layer parallel to the stone wall was assumed as illustrated in Figure 1b. It must be noted that the connection between gunite and masonry was assumed to be fixed.

The properties of the materials, which were considered, are given in Table 1.

Table 1: Material assumptions.

Material	Modulus of Elasticity (GPa)	Poisson ratio	Density (kg/m^3)
Stone	8.657	0.15	1944
Concrete/Shotcrete	26.487	0.20	2400

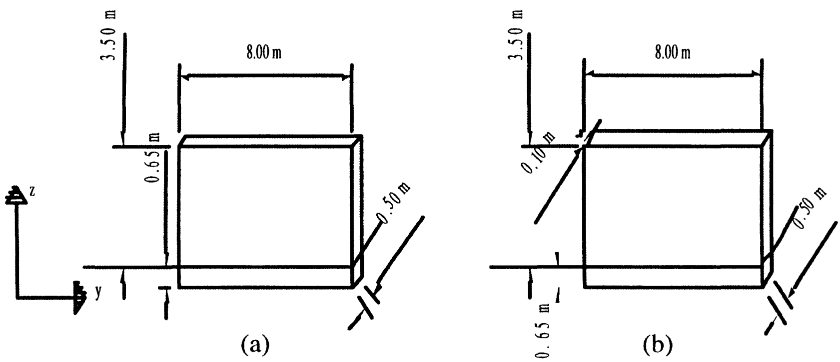

Figure 1: Geometry of models without (a) and with (b) gunite.

Three dimensional, solid finite elements with three translational degrees of freedom per node were used for finite element modeling. Based on the assumption that the wall is part of a building, spring elements with two degrees of freedom were used for modeling the connection with the perpendicular walls. The use of two dimension finite elements (plate and shell) for modeling leads to an economical model but with less accuracy.

The following models were examined in order to compare the behavior of the stone, concrete and the composite structure under static and dynamic loading:

- **Models with three dimensional, solid finite elements.**

Ia Model with stone.
The model has 2458 elements and 3404 nodes. All the elements belong to the material of stone.
Ib Model with concrete.
The number of elements and nodes are equal to model with stone and all the elements belong to the concrete material.
Ic Model with shotcrete (gunite).
The model has 3238 elements and 4242 nodes. The new 780 elements belong to the material of shotcrete and the rest elements belong to the stone material as in case A1.

- **Models with multilayers.**

In order to compare the results between two and three dimensional finite models, a model with myltilayers finite element was considered.
IIa Model with shotcrete (gunite)
Two layers (multilayers) were used with membrane and bending capabilities. Six degrees of freedom (three translations and three rotations) per node are considered. The thickness of the first layer (gunite) is equal to 0.10m and the thickness of the second layer (stone wall) has taken equal to 0.50m (the data correspond to a practical application Figure 1b)

4.2 Analysis

In order to examine the behaviour of the previous example the wall was subjected to static analysis were only the weight of the structure was taken into account. Then the structure was also subjected to response spectrum analysis. As it is well known the dynamic behaviour of a linear elastic system can be described through its dynamic characteristics. Using frequency analysis the possible ways of the eigenmodes and the corresponding frequencies are calculated. So it is important to use a reliable model taking into account all the details which affect the system and are the cause of the damage that lead to collapse. The calculation of the dynamic characteristics of the structure is a good way for a reliable estimate of, the frequency range in which an earthquake excitation will seriously affect the structure. It is also important for the identification of the specific points of failure of the structures which lead to the proper selection of a suitable strength restoration method, e.g. Sherif.[3]

Dynamic loading is considered by means of modal analysis techniques based on appropriate design spectra adopted by most design specifications.[4] Using the design earthquake spectrum the statically expected earthquake is taken into account. This spectrum which describes the acceleration for different periods and depends on the characteristics of the region and of the building (i.e. type of foundation, the damping defined by its structural system) is important for masonry construction. According to the New Aseismic Design Specification of Greece[5] which is in accordance with the European codes, the seismic design spectrum is given by the equation (1).

$$R_d(T) = \frac{A\gamma_I b_d(T) n\Theta}{q} \quad (1)$$

where $R_d(T)$ = the horizontal components of the earthquake design forces (in m/sec^2).
A=0.24 g=2.4 m/sec^2 seismic acceleration of the ground
γ_I=1.00 coefficient of importance of the building
$b_d(T)$ the modified elastic spectrum
T the eigenperiod in sec

In our case the characteristic period of the seismic design spectrum is taken equal to 1.2 sec.
n=0.70 corrective damping coefficient
q=1.50 coefficient of seismic behavior
Θ=1.00 coefficient of the foundation material.

4.3 Results and Conclusions

Form frequency response analysis the eigenfrequencies were calculated for all models and the first ten of them are given in Table 2. Indicative the first and ninth eigenmode for model Ia and third and fifth for model Ic are shown in Figures 2 and 3 respectively.

Table 2: Eigenfrequencies (cycles/sec) for beam, solid and shell multilayer finite element model of wall with shotcrete.

Models	**3D Solid elements**			**Shell multilayer**
Mode	Ia	Ib	Ic	IIa
1	5.36	8.17	7.34	4.73
2	11.85	17.49	15.60	8.04
3	21.27	30.27	25.80	10.42
4	21.98	33.44	26.97	11.92
5	22.76	35.63	28.72	12.21
6	27.12	40.77	34.96	14.72
7	33.98	44.27	39.42	15.22
8	36.03	52.57	44.91	16.38
9	37.08	58.73	47.06	16.49
10	41.18	60.50	48.82	18.42

From dynamic analysis and for seismic excitation first in X direction (the out of plane) and second in Y direction (the in plane), the participation factors

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were calculated. These factors (see, Table 3) indicate the importance of out of plane behavior and its contribution to the overall oscillation.

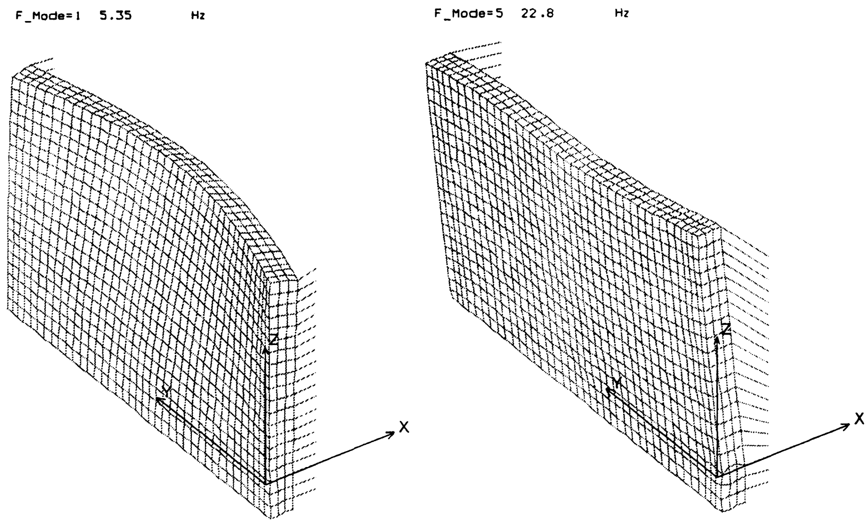

Fig. 2: First and fifth eigenmode of model Ia.

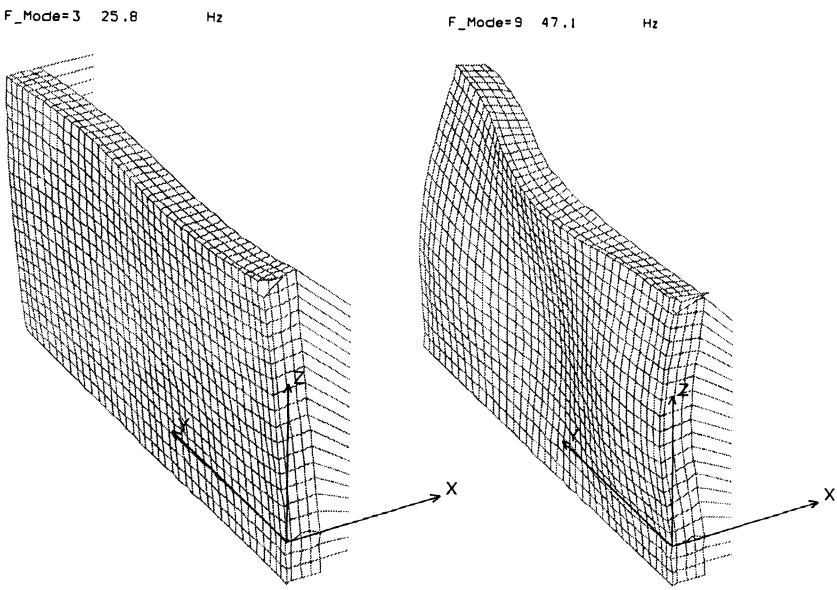

Fig. 3: Third and ninth eigenmode of model Ic.

Table 3: Participation factors (%) for seismic excitation in X and Y direction

Models / Modes	Concrete (Ib)		Masonry (Ia)		Gunite (Ic)	
	X	Y	X	Y	X	Y
1	42.36	0.00	40.71	0.01	65.70	0.00
2	0.006	0.00	0.01	0.00	0.03	0.00
3	4.66	0.02	3.57	0.14	0.99	0.02
4	13.09	0.13	12.26	0.01	2.42	0.13
5	0.47	85.20	0.43	84.94	23.13	85.20
6	0.02	0.00	0.01	0.00	0.04	0.00
7	0.01	0.00	0.00	0.00	0.05	0.00
8	0.66	0.00	0.63	0.00	0.01	0.00
9	38.22	14.61	36.78	14.57	6.18	14.61
10	0.50	0.04	5.72	0.34	1.46	0.04

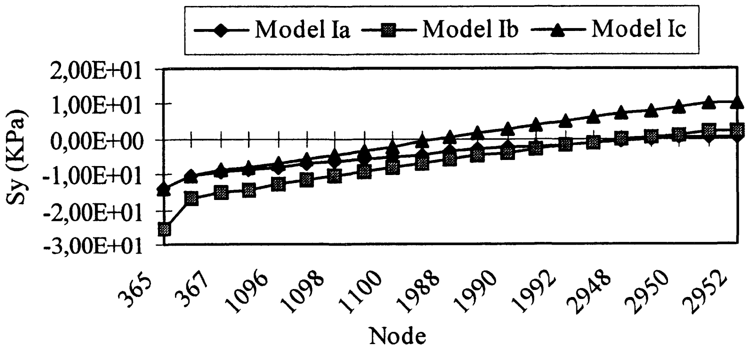

Fig. 4 :Stress Sy from static analysis (vertical section)

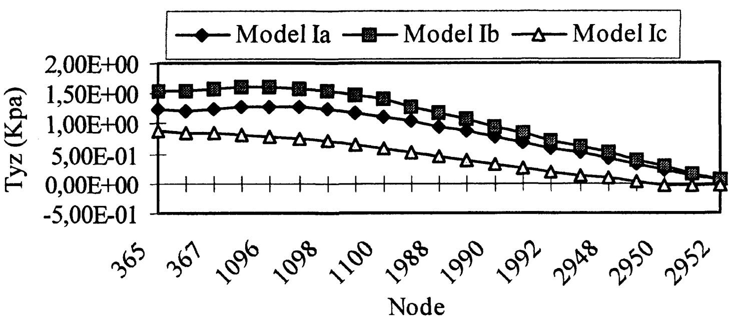

Fig. 5: Stress Tyz from static analysis (vertical section)

From stress analysis the influence of gunite on the stress distribution of the stone wall are investigated. The behavior of stone and concrete is analogous, as linear elastic material behavior was considered for both of them. The present of the additional layer of gunite influence the static also dynamic results in out and in plane direction. Some indicative results are given in Figures 4-8 from static and dynamic analysis and they refer to a vertical section on the inner part of the stone wall (node 365 is on the base and 2952 on the tope of the wall).

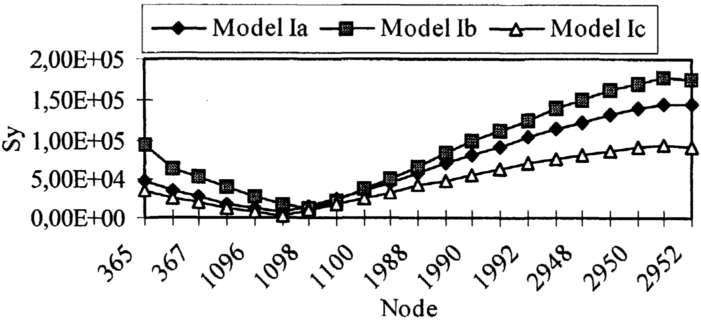

Fig. 6:Stress Sy from dynamic analysis in x direction

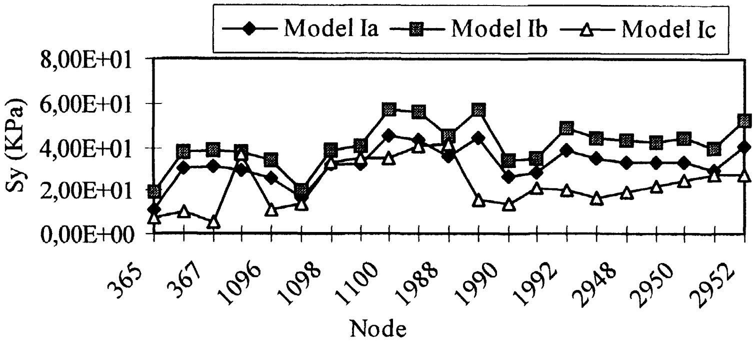

Fig. 7: Stress Sy from dynamic analysis in y direction

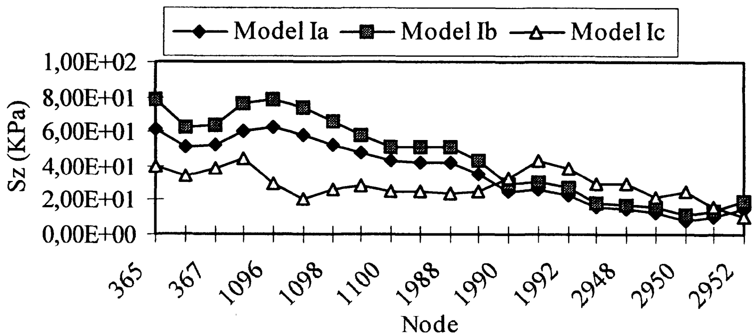

Fig. 8: Stress Sz from dynamic analysis in y direction

In case to have a spherical view of the problem it was also examined a combination of static and dynamic loading according the codes[5] where the influence of seismic excitation simultaneously in the two directions are taken into account. The vertical direction was not obtained, as our example is not height enough. Four cases of these combinations are shown in Figure 9, for the model with gunite (Ic.)

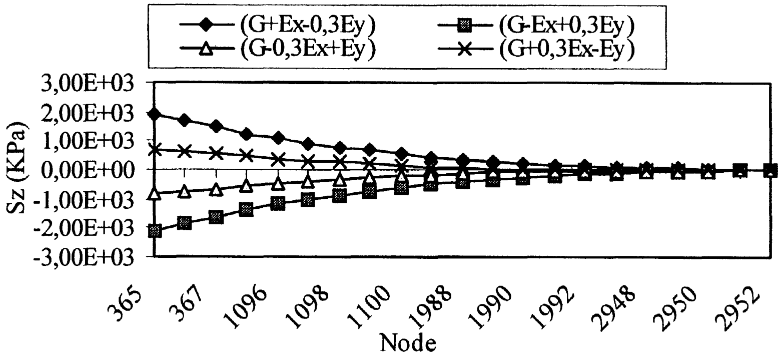

Fig. 9: Stress Sz from combination of static and dynamic analysis (Model Ic)

From the numerical investigation which is briefly described here the following conclusions can be drawn. A mantle of shotcrete reduces, in general, the stress burdening of the structure. The extend of this beneficial influence depends on the loading and on the geometrical form of the structure. A double mantle would be more effective, but its construction is not always feasible. Finally one should notice that all previous results are based on the assumption of a perfect bonding between the existing structure and the mantle reinforcing layer. This assumption permitted us use linear structural analysis techniques. Nevertheless one expects that debonding and delamination effects will reduce the cooperation between the two structural elements and thus, the effectiveness of this intervention technique. A nonlinear analysis for the study of these effects is left open for future investigations.

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