Transactions on the Built Environment vol 15, © 1995 WIT Press, www.witpress.com, ISSN 1743-3509

Comparative study of the seismic response of stone and brick masonry buildings

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Abstract

Static and eigenvalue FEA of geometrically similar brick and stone-masonry buildings show that the former are seismically much more vulnerable. The reason is not only the lower material strength and higher mass of the walls, but mainly the lack of horizontal restraint by rigid floors in the out-of-plane direction.

1 Introduction

Two or three-storey stone or brick masonry buildings constitute the vast majority of the building stock in the seismic-prone areas of Southern Europe. Most of them were constructed in the early part of this century or before and are part of the architectural and cultural heritage, often forming the historic urban nuclei of cities and towns. Because of the inherently low strength of masonry, in seismic regions earthquakes are a dominant threat to the integrity of these buildings.

In this paper the seismic response of stone and brick masonry buildings is compared analytically, using the F.E.M. Three actual traditional two-storey plus basement buildings are considered, with 0.60m thick stone masonry walls and timber floors and roof. Karantoni and Fardis [1] presented details of these buildings, and a comparison of their seismic damage with the magnitude and the direction of extreme principal tensile stresses, as predicted from linear elastic FEA under static lateral loads equivalent to the recorded ground motion. In [1], the comparison with the observed damage validated linear elastic FEA as a tool for the static seismic response analysis of this class of structures and has cast serious doubts over the validity of the wide beam and column analogy and other simpler analysis approaches often used in practice for such buildings. Three companion brick masonry buildings are considered also herein, with the same geometry of the walls in plan and in elevation as the stone masonry buildings. However, as it is typical in more recent masonry constructions, the floors and the roof consist of 0.15m thick concrete slabs. For this reason, interior walls of the brick masonry buildings are continued to the second storey. The thickness of brick walls is equal to 0.30m and the elastic modulus is 4GPa. As the elastic modulus of stone masonry is taken equal to 2GPa, the product of modulus times thickness, which is a measure of wall stiffness, is the same in both cases.

2 Characteristics of the Dynamic Response

The shapes and periods of the first few significant natural modes of vibration of the two types of buildings were computed and compared. In the brick masonry buildings mode shapes are controlled by the constraint of the horizontal displacements of the floors and the roof imposed by the slabs. Accordingly, in each one of the first few significant modes every point of the same storey (and usually every point of the structure) moves in phase in a single horizontal direction. Figs. 1 and 2 show on the left-hand-side the shapes of the most significant (in terms of modal mass) mode in each of the two horizontal directions, X and Z. In buildings 1 and 2 these modes are almost purely translational in directions X and Z, while in building 3 the irregularity in plan and in elevation created by the concentration of load-bearing walls and the setback of the second storey on the right-hand-side induces a strong torsional character. Overall the mode shapes resemble those of multistorey frame buildings with rigid floors. On the contrary, the mode shapes of the stone masonry buildings with timber floors are dominated by the out-of-plane vibration of the free-standing walls: In all six modes shown on the right-hand-side of Figs. 1 and 2, parallel walls vibrate in phase in the out-of-plane direction, with very little in-plane motion of the transverse walls. The next significant mode in each direction, not shown in Figs. 1 and 2, involve in-phase in-plane displacement of the walls which are parallel to one of the two

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directions X and Z, along with out-of-plane displacements of the transverse walls but in the opposite sense (i.e. out-of-phase). In the absence of rigid floors, stone masonry buildings may develop also higher, but relatively insignificant modes, involving shear distortion in plan, out-of-phase out-of-plane displacements of parallel walls, and others, which are not present in the brick masonry buildings.

The difference in mode shapes of the two types of buildings is due not only to the constraint imposed by the rigid floors to the former, but also to the fact that in the stone masonry buildings 90% of the total mass resides in the walls (vs. 58% of the brick masonry ones), increasing therefore the importance of out-of-plane vibrations. The large (factor of 3.0) difference between the natural periods of the two types of buildings is not due to the different stiffness of the walls (the product of wall thickness times Modulus is the same) but a) to the different total mass (1.37 times higher in the stone masonry buildings, due to the about twice heavier walls) and mainly b) to the different modes of vibration: flexural out-of-plane modes are more flexible and longer-period than in-plane ones, and, in addition, the introduction of displacement constraints by the rigid floors reduces significantly the natural periods.

The dynamic response characteristics of the two types of buildings considered show that old and traditional stone masonry buildings with timber floors are much more vulnerable to earthquakes than more recent brick masonry buildings with rigid floors: Their 3-times longer periods of vibration places them in the nearly constant acceleration plateau of most strong ground motions, and especially of the near-field ones typical of Southern Europe. In addition, as shown by the static analysis results of next Section, their predominant mode of vibration, i.e. out-of-plane bending, makes them much more liable to seismic damage.

3 Extreme Stress Conditions in the Walls from Static Analyses

Stresses in the walls of the six of buildings were computed, for a static application of a uniform response acceleration of 0.4g separately in the two horizontal directions and in combination with the gravity loads. The same FE discretisation was used as in the eigenvalue analyses. Maximum wall surface stresses σ_x, σ_y, τ_{xy}, at each F.E. integration point were compared with the failure criterion of masonry under biaxial stresses, and the value of an equivalent stress σ^* was computed at each point and for each load combination, such that stresses (σ_x/σ^*, σ_y/σ^*, τ_{xy}/σ^*) cause failure of the masonry. The value of σ^* measures the fraction or multiple of the failure condition to which response stresses (σ_x, σ_y, τ_{xy}) correspond. For stone masonry the isotropic multiaxial failure criterion [2] was applied, with a compressive strength f_{wc} of 1.7MPa, representative of the rubble masonry construction and the lime mortar of the three buildings, and a tensile strength f_{wt} equal to 0.085 f_{wc}. Mean values of σ^* over the two surfaces of the external walls of the three masonry buildings are given in Table 1, separately for the walls which are parallel to the earthquake direction and for those which are normal. The mean over each wall extreme value of σ^* for all four earthquake directions considered is also given, denoted as "independent" of seismic direction.

Table 1, as well as contours of the σ^*-values over each wall, suggest that the most vulnerable part of the stone masonry buildings is the second storey of the walls in out-of-plane bending due to the normal component of the earthquake. This earthquake component causes the most severe stress conditions in the walls parallel to it near the junctions of exterior walls, due to transfer of horizontal forces from one wall to the other. Last but not least, the average and the local maxima of the σ^* values signify widespread, cracking and failure by overturning.

For direct comparison with the stone masonry results, stresses of the brick masonry buildings were assessed using again the isotropic failure criterion in [2], with $f_{wt}/f_{wc}=0.085$ but with $f_{wc}=6$MPa, a value representative of recent clay brick masonry with a rich cement-lime mortar. Values of σ^* in Table 1 and the corresponding contours over individual walls are much lower than those for stone masonry and well below cracking and failure. To remove the effect of the 3.53 times higher strength and that of the 37% lower mass and inertia forces in the brick masonry buildings, the values in Table 1 have to be multiplied by 3.53x1.37 = 4.85 before comparing to those of stone masorny. But even after this conversion (which neglects the 4 times higher section modulus of stone masonry against out-of-plane bending), brick masonry stresses are on the average about half those of stone masonry for the walls which are parallel, or about 5 times lower for those which are normal to the earthquake direction or independently of it. Finally, contrary to what happens in the stone masonry buildings, it is the lower part of the walls parallel to the earthquake which is most critical (in-plane diagonal tension-compression), rather than the upper part in out-of-plane bending.

The anisotropic failure criterion of Mann and Müller [3] and Dialer [4] was also used for the assessment of the multiaxial stresses in the brick masonry, as

Table 1: Average over all exterior walls equivalent stress σ^* at wall surface

Eartquake direction relative to walls	Material & biaxial failure criterion								
	Stone			Brick					
	isotropic [2]			isotropic [2]			anisotropic [3],[4]		
	Storey			Storey			Storey		
	basement	1st	2nd	basement	1st	2nd	basement	1st	2nd
parallel	0.78	0.77	1.03	0.11	0.09	0.06	0.59	0.39	0.20
normal	0.84	0.61	1.37	0.05	0.04	0.05	0.43	0.26	0.17
independent	1.15	0.95	1.65	0.12	0.09	0.07	0.61	0.39	0.21

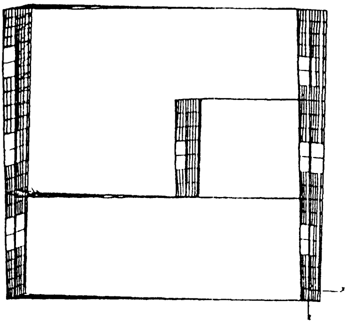
far more representative than the isotropic criterion in [2]. The cohesion and the friction coefficient along bed and head joints were considered equal to 0.2MPa and 0.7 respectively, while the smeared tensile strength of $0.085\ f_{wc}=0.51$MPa was attributed to the bricks alone. As shown in Table 1, the same stress pattern is assessed as several times more critical by the more realistic anisotropic failure criterion than by the isotropic one used above for comparison with the stone masonry. Still, though, wall stresses are well below failure, even in the most critically stressed lower part in the in-plane direction. The conversion factor to be applied to the brick masonry results to make them comparable to those for stone masonry, may be taken in this case as the mass conversion factor, 1.37, times the ratio of the cohesion to the tensile strength of masonry, i.e. 0.2/0.085x1.7=1.38, i.e. overall 1.9. With the application of this magnification factor, equivalent stresses in the brick masonry buildings become comparable to those in the stone masonry ones when the earthquake is parallel to the walls, but stay significantly lower when it is normal to them. This demonstrates the beneficial effect of the slabs on the out-of-plane resistance of walls.

4 Conclusions

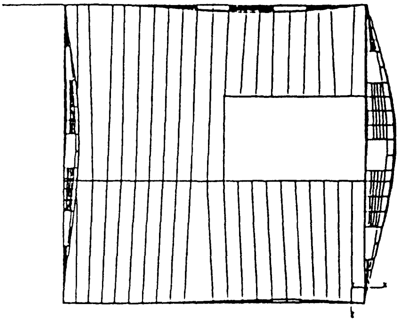
Linear elastic static and dynamic response analyses show that the seismic response and behaviour of old, traditional two-to-three storey stone masonry buildings with timber floors and roof are fundamentally different from those of recent-type brick masonry buildings with concrete slabs. In the former the walls represent about 90% of the total mass and are quite vulnerable in the out-of-

Building 1

Brick/Slabs: T=0.08 s.

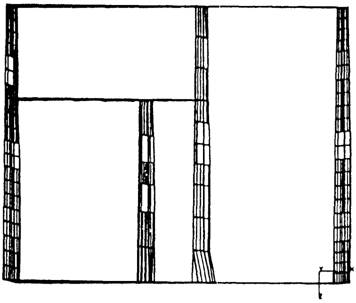


Stone: T=0.235 s.

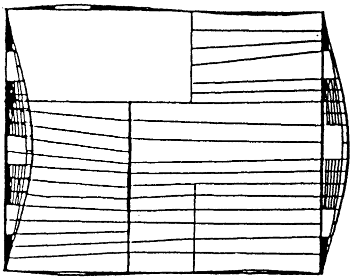


Building 2

Brick/Slabs: T=0.085 s.

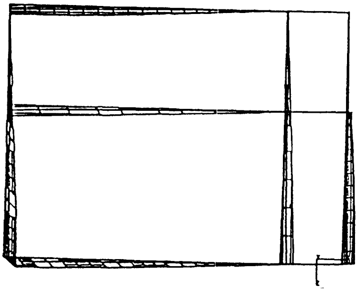


Stone: T=0.24 s.



Building 3

Brick/Slabs: T=0.06 s.



Stone: T=0.19 s.

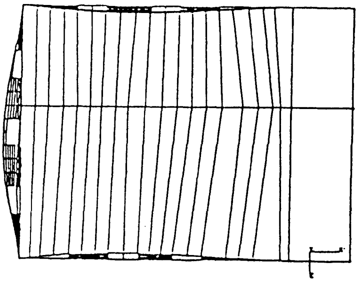
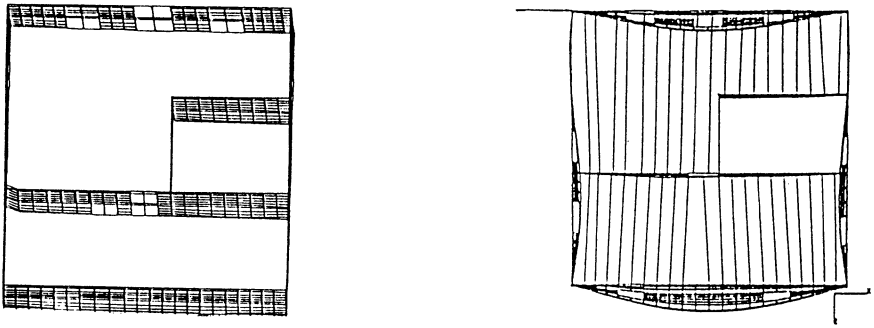


Figure 1: Periods and shapes in plan of 1st significant mode in X direction

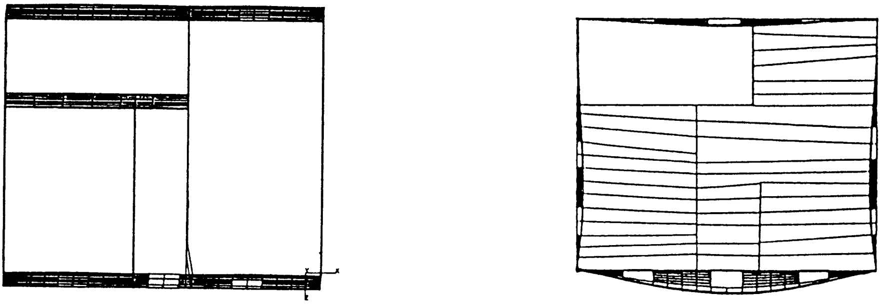
Building 1



Brick/Slabs: T=0.09 s.

Stone: T=0.22 s.

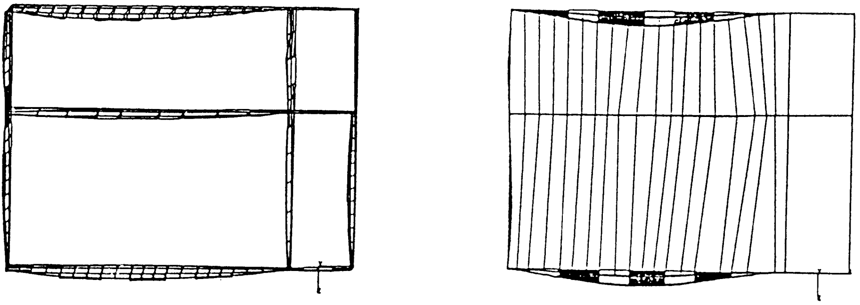
Building 2



Brick/Slabs: T=0.08 s.

Stone: T=0.26 s.

Building 3



Brick/Slabs: T=0.04 s.

Stone: T=0.24 s.

Figure 2: Periods and shapes in plan of 1st significant mode in Z direction

plane direction under their own inertia forces. Moreover, their linear elastic seismic response can be reliably predicted only through relatively sophisticated approaches, such as the F.E.M with a large number of DOFs. In brick masonry buildings with rigid floors, the latter restrain out-of-plane bending and transfer transverse wall inertia forces to the parallel walls. Therefore the walls, and especially their lower part, suffer mainly from in-plane stresses. The application of different multiaxial criteria to assess failure on the basis of the calculated stresses shows that the higher strength of good quality brick masonry in tension and compression parallel and normal to the joints cannot be fully exploited in the presence of shear stresses, due to sliding failure along the joints. So, the main reason for the superior seismic resistance of brick masonry buildings is the beneficial effect of rigid floors, rather than the higher material strength and the lower total mass. This suggests introduction of rigid concrete slabs in place of the flexible timber ones, as a very effective strengthening measure for old stone masonry buildings, without any intervention to the walls themselves.

Acknowledgement

The support of the European Centre for Earthquake Forecasting and Prevention and of the Earthquake Planning and Protection Organisation in Athens, Greece, is greatefully acknowledged.

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