DAMAGED MASONRY STRUCTURES AND THEIR RESIDUAL SHEAR CAPACITY BY FRICTION EFFECT

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SUMMARY

The majority of the old masonry buildings present large cracks, after very strong motions. However, the most of these objects didn't reach their general collapse. The same behaviour aspect was remarked at the ancient stone columns, without mortar. This proves the friction effect during earthquake response oscillations. The equivalent base force for this phenomenon can be named residual base shear force. These aspects are presented in the paper. The paper includes an adequate form for the differential equation system, proposed by the author, also. This formulation tacks into account the friction effect, by introducing of the friction functions. The author made some experimental researches, using physical models on the shaking table, for the determination of the friction factor variation in the dynamic range. The special experimental results and theoretical developments will lead to a better evaluation of "residual" safety factors of the old and damaged masonry structures.

On the other hand, the design friction factor values given in the design codes for the new masonry structures can be corrected with accurate ones. Finally, one is presented a simplified approach for the seismic risk assessment of the old and damaged masonry structures, based on the residual friction capacity.

INTRODUCTION

Structural engineers studied to design new buildings and facilities. The basics of the Structural Sciences are based by the hypothesis: a. The structural system is a continuum solid; b. The relation between stress-deformation is linear/non-linear; c. All connections can be simple, hinged or embedded only. But, the old damaged masonry buildings do not respect these assumptions. Their major cracks (inclined or vertical) mean their fragmentation; and the Theory of the Elasticity is not valid for discontinuities!

The superior parts of the fragmented walls slide over inferior ones; the effective connection can be the friction effect only and not "classical" one. The experimental investigations confirmed this "residual base shear capacity" in the case of the significant earthquake actions. These features of the old damaged masonry buildings invalidate the use of the Mechanics of Continuum Solids. A new Mechanics are necessary: the Mechanics of the Systems with Rigid and Deformable (Elasto-Plastic) Members. The last steps in the Multibody Rigid Dynamics field shown the advances in other domains of the Engineering. Of course, the Structural Theory (for the civil engineers) do not must remain in the second place!

This paper means some of the needed steps in this direction. The author's desire is to offer a realistic model for a "special" structure class: the law height and old damaged masonry buildings. The use of a sophisticated program, based on the Distinct Element Method – the best approach for such cases, can be too expensive in many situations. Nevertheless, the development of a Coupled System Dynamics with Rigid and Elasto-Plastic Members is necessary for usual earthquake shear capacity assessments.

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A SHORT REVIEW OF THE SEISMIC BEHAVIOUR OF THE OLD MASONRY BUILDINGS

The oldest edifices (historical/architectural monuments, especially) were build from natural stone blocks or from ceramics (bricks). Walls were covered with brick arches and vaults (sometimes, with metal girders) or domes for buildings. Researchers, (Meli and Sanchez-Ramirez 1996) gave typical example of the same damaged building. Each "fragment" (who is a quasi-rigid body) will be acted by gravitational and earthquake forces, the vault (or arch) becoming a system of rigid bodies, Fig. 1.

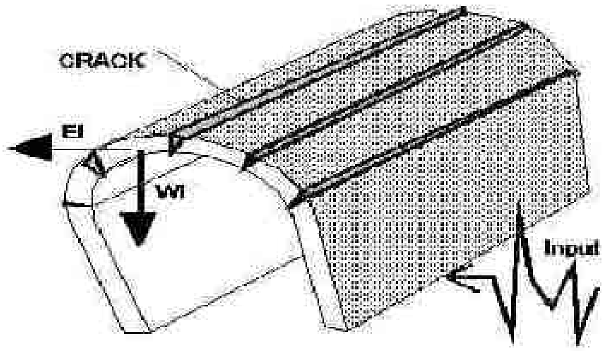

Fig. 1. Breaking up of a vault under earthquake actions. (After Meli and Ramirez-Sanchez)

Some less old masonry buildings kept curved "horizontal" members and others not. Their floors remained "non-diaphragms" even if these subsystems were replaced with one-directional floors. It is about of the timber floors with their transversal beams. A reduced scale model of an ancient stone porch was tested on a shaking table (Manos and Demosthenos 1996), Fig. 2. This system was build without mortar. Consequently, the slips of each rigid body leaded to the final shape of columns. The mechanical idealisation can be similar with the previous one: slipping and rocking rigid bodies.

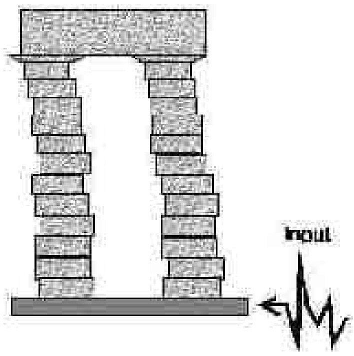

Fig. 2. Deformed shape of stone small model on a shaking table. (After Manos and Demosthenos)

Other researchers fond the equivalent idealisations for newer buildings having rigid piers and weak connections of the floors with bearing walls. Typical idealisation is given in Fig. 3.

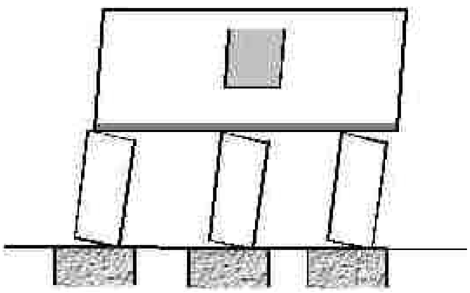

Fig. 3. Multibody system mechanism. (After Anici)

Another old masonry buildings are churches. These objects contain many curve members: arches, vaults and domes, (circular at the Byzantine-orthodox churches or ogival at the catholic ones). Prof. Cismigiu shown the typical fragmentation of the orthodox churches at the earthquake actions, (Cismigiu & Cismigiu 1996), Fig. 4.

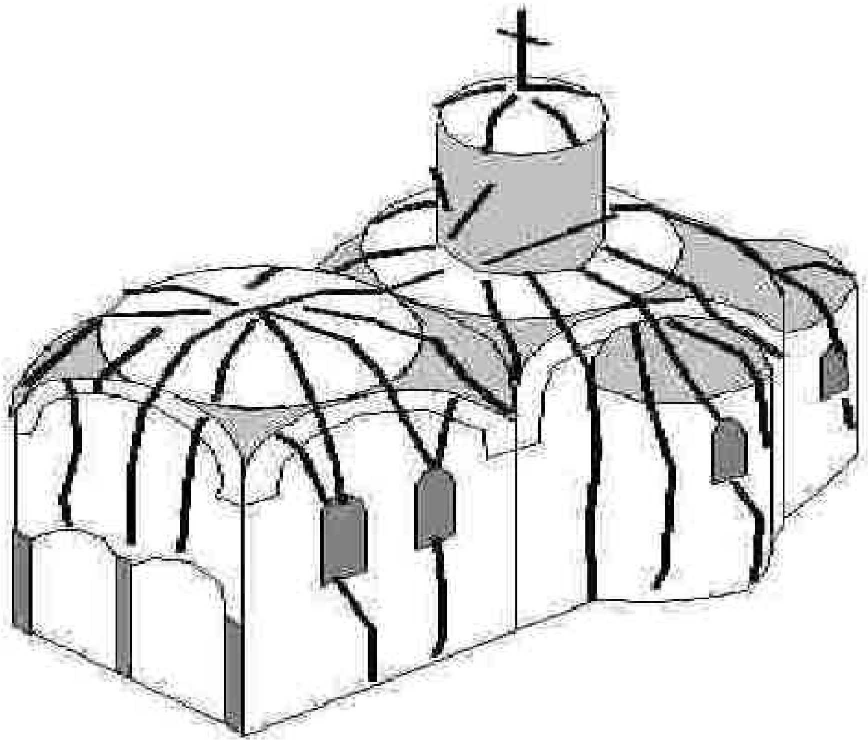

Fig. 4. Typical fragmenting of the orthodox churches in Romania. (After Cismigiu and Cismigiu)

DIFFERENTIAL EQUATION SYSTEM FOR SYSTEMS WITH CRACKS AND FRACTURES

Lets look the masonry house from Fig. 5. One can remark the fully inclined cracks on the wall panels at the first story and horizontal crack between this level and the next one. The superior story can slide at the major earthquake action, if the inertia force exceeds the friction dynamic force. One can include all small slidings in the first level of the fractured/cracked members in this idealisation, (Olaru 1997).

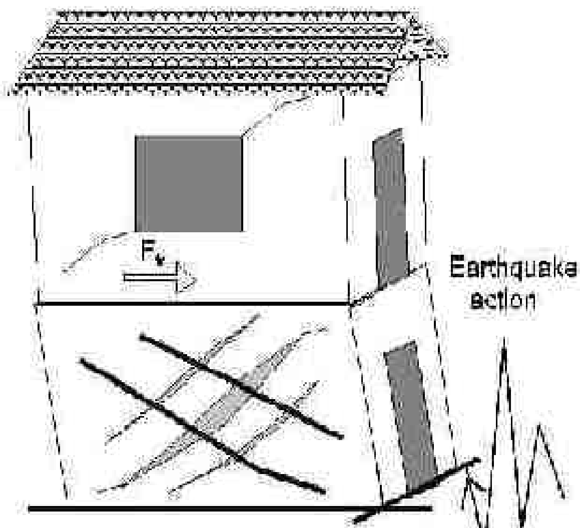

Fig. 5. Concentration of the damages on the ground floor of a masonry house. (Olaru)

The well-known matrix equation (1) can't remain the same, in these new coupling conditions, (Olaru 1998). The main modification of the mathematical representation will be the introduction of the friction forces, fi. These components can be written for "i" DOF as:

$$\mathbf{M}\mathbf{x}''+\mathbf{C}\mathbf{x}'+\mathbf{K}\mathbf{x} = -\mathbf{M}\mathbf{y}'' \tag{1}$$

$$f_i = \Gamma_i(1,2,...,n) \tag{2}$$

$$\Gamma_i = (m_i g)\,\mathrm{f}_d \tag{3}$$

Where: **M** - mass matrix; **C** - damping matrix; **K** - stiffness matrix; **x"** - response acceleration vector; **x'** - response velocity vector; x - response displacement vector; **y"** - ground acceleration vector (computed as **y"**=**1a**; *G*i and *m*i - weight and mass of the "i" DOF; fi(1, 2,...,n) - friction function of the parameters; *g* - gravitational acceleration. The friction vector, **f** will include all components fi (i=1,2,...,n). Finally, the expression of the friction vector can be written as:

$$\mathbf{f} = [\mathbf{M} * g][\mathbf{s}_f][\mathbf{f}_d] \tag{4}$$

The vector **s**f is one of the so-called "condition vector". This matrix has the elements equal with 1, if the connection works as a friction bearing, while all another elements are equal with 0. The second modification must be done in the mass matrix, **M** and in the rigidity matrix, **K**. Some masses can be redistributed because of the lost continuity for some structural members, new matrix being **M***. In the same time some elements in the **K** matrix become equal with "0" because of appearance of the "gaps", new matrix being **K***. The transformation can be done using the "condition matrix" **S**m , **S***m and **S**k:

$$\mathbf{M}^* = \mathbf{M}\mathbf{S}_m + \mathbf{S}^*{}_m \tag{5}$$

$$\mathbf{K}^* = \mathbf{K}\mathbf{S}_k \tag{6}$$

The initial diagonal matrix **S**m has the values 1 for main elements and 0 for the rest, while the diagonal matrix **S***m has all elements equal with 0. If the mass redistribution appears, then for a mass "tt" who will added to the mass "ss": a. the correspondent element of the mass "tt" in the matrix **S**m will be equal with 0; b. the correspondent element of the mass "ss" in the matrix **S***m will be equal with mass "tt". If the structural members are active, then in the diagonal matrix Sk the correspondent element will be equal with 1; contrary, the value will be 0. Other modifications in the equation system will result, if it will take into account the possibility of the changes in the damping matrix, **C** :

$$\mathbf{M}*\mathbf{x}''+\mathbf{C}*\mathbf{x}'+\mathbf{K}*\mathbf{x}+\mathbf{f} = -\mathbf{M}*\mathbf{y}'' \tag{7}$$

The general formula (7) are valid for all old masonry structures, having some piers damaged and others not.

SHAKING TABLE TESTS FOR THE DETERMINATION OF A FRICTION FUNCTION FOR THE OLD MASONRY

The determination of the function **Γ**(β1, β2, …, βn) needed an experimental research program. Two simple masonry models were been tested at INCERC Iasi, Romania, Fig. 6. The reduction geometric scale was 1:3 for the both specimens. Brick class was C75 and mortar class only M4, because the similarity with old masonry buildings. Each model had two levels and two “U” pierces parallels with horizontal earthquake action. One model (“older” one) had the wood floors and another (“newer” one) the RC floors. The same actions were been applied for the both, by their simultaneous placing on the shaking table.

Fig. 6. Masonry models tested on a shaking table. (Olaru)

The test program included various tests: a. preliminaries; b. effectiveness; (both containing vibrations of earthquakes and sinus train waves with varied frequencies). In primary phase, one obtained the major cracks in the wall pierces, concentred on the ground story. The sliding of the first floor was obtained for wood, also. In the second phase, the “drifts” of the rigid bodies near the major cracks and of the second level (as rigid body) were measured. The limit of the friction action was admitted for a story drift, s equal with 0.2 mm, similar with the RC large panels. The dynamic friction function, *f*d derived from the correlation input frequency, *f* (Hz) – *s* (0.2mm). The scheme of the determination is given in Fig. 7.

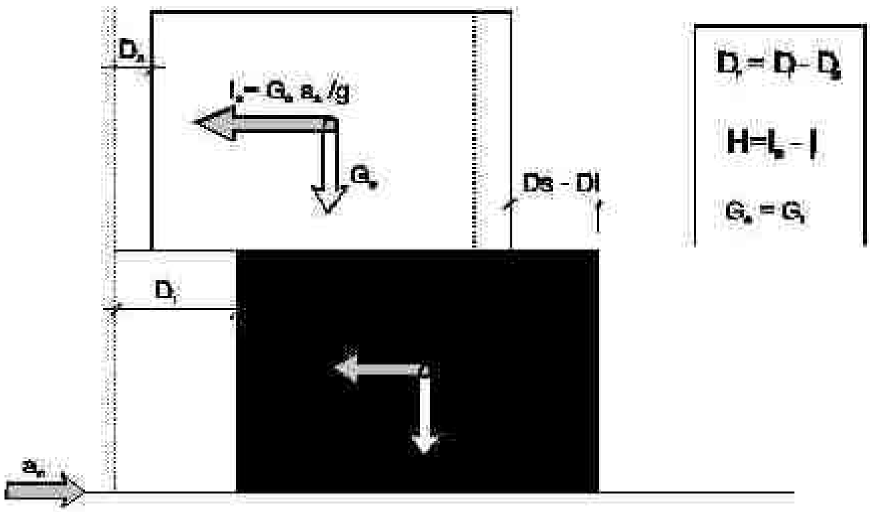

Fig. 7. Mechanical model for evaluation of the dynamic friction function. (Olaru)

The s value is the difference between horizontal displacements of the two bodies (superior, *d*s and inferior, *d*i). The limit horizontal force, *H* results from the difference between the two correspondent accelerations and from the superior sliding mass, *M*s. The axial force, *N* is equal with *G*s. The relationships are the following:

$$s = d_s - d_i \tag{8}$$

$$H = [G_s a_s - G_i a_i / g] \tag{9}$$

$$f_d = H / N = [a_s - (G_i / G_s) a_i] / g \tag{10}$$

One retained here the graphic representation of the dynamic friction function for the model with wood floors, Fig. 8. The author's tests on the shaking table, for weak masonry structures, shown a dependence of the prevalent site earthquake frequency, fg and of the structure eigenfrequency, f1s for the friction function Γ(β1,β2,…, βn), Fig. 9. The minimum values is 0.15 for the "tuning" domain and about 0.20 for fg /f1s > 2.0. Consequently, one can consider from practical cases a dynamic friction coefficient fd = 0.15,…,0.2, (smaller than the static friction factor, fs), (Olaru 1999).

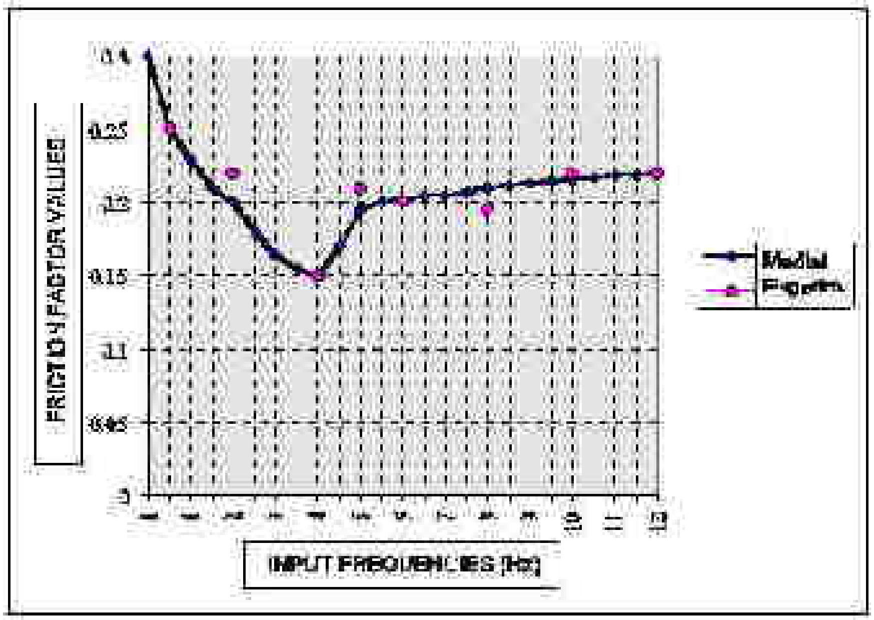

Fig. 8. An experimental friction function for old masonry structures. (Olaru).

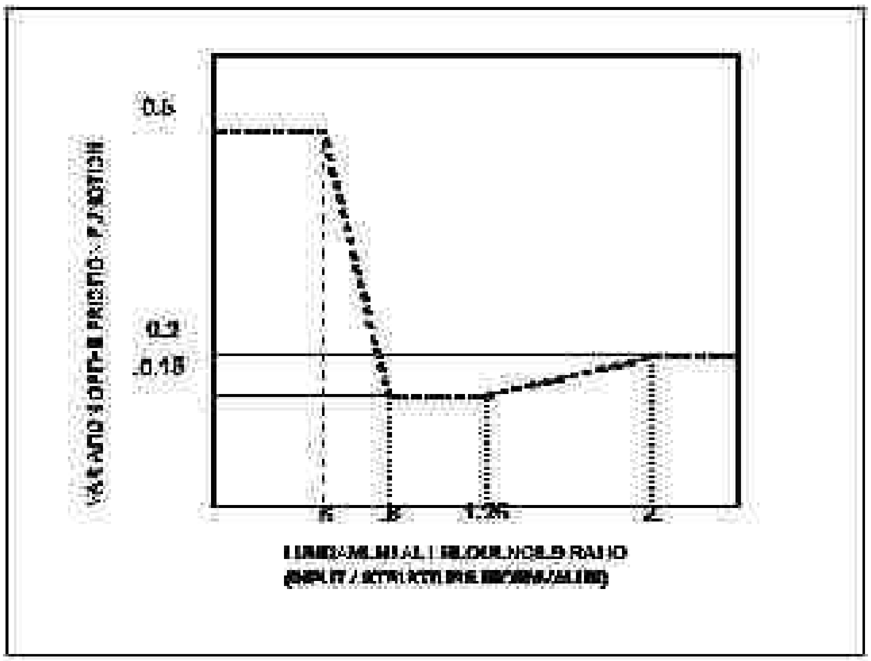

Fig. 9. Normalised friction function for old masonry structures. (Olaru)

A SEISMIC LOAD CAPACITY ASSESSMENT BASED ON THE FRICTION EFFECT

Three kinds of verifications are necessary: a. general stability; b. maximum displacements; c. strength capacity. The safety factors for each case will be established by analysis. The first two points can be done using the relations given in the previous author's paper, (Olaru 1998). More, one need search the values of the relative displacements between wood/metal beams on the bearing walls, to prevent the local collapses. The main "rectification" will be for strength capacity evaluation, because of the friction effect consideration. This approach considers two shear force capacities for old damaged buildings, based on: a. friction effect for members with fractures; b. mechanical resistance for continuos members, (residual, yet). The simplified relations are the following:

$$V_f = \sum_i V_{f,i} = \sum_i [N_{f,i} f_d] \tag{11}$$

$$V_c = \sum_j V_{c,j} = k_1 \sum_j \{Min[V_{ec,j}; V_{dt,j}; V_{s,j}]\} \tag{12}$$

$$V_{ef} = k_2 [V_f + V_c] \tag{13}$$

$$k_1 = G[\sum_k S_k][\sum_l D_l] \tag{14}$$

$$k_2 = \Omega(type\_floor) \tag{15}$$

Where: Vf - total friction base shear force; Vf,i - base shear force of damaged "i" member; Nf,i - axial force of damaged "i" member; fd - friction factor (see normalised friction function); Vc - total residual base shear force for continuous members; Vc,j - residual base shear force of continuous "i" member; Vec,j - shear force of member "i" associated with residual bending capacity; Vdt,j - shear force of member "j" associated with residual diagonal tension capacity; Vs,j - residual shear force of member "j"; k1 - correction depending on the site condition (G), structural conformations (Si), structural damages (Di) - see (Olaru 1998); Vef - total base shear capacity of damaged structure; k2 - correction factor depending on the effective diaphragm function of the floors (smaller than 1, generally), about: 0.75 for normal wood beams (on the horizontal earthquake action), 0.5 for parallel wood beams, 0.7 for normal vaults, 0.6 for parallel vaults; 0.8 for domes.

How can establish the "residual" ultimate stress values (f*c for compression, f*s for sliding shear and f*dt for diagonal tension) ? A large field of values will lead to a great-scattered aspect. The author thinks that one must select the residual capacity stresses of the most damaged regions of the structural members. In these places the measurements are necessary. If a reach database (about the residual capacity stresses of the old masonry) exists, one can use their medium values in the usual seismic load capacity assessment. Such medium residual values are given in the draft version of a Romanian code for historical monuments, (Mironescu 1999). On the other hand, sometimes one can find walls with big caverns or which have some crushing zones. These sections do not be considered in safety analyses. If the majority of the wall piers are strong (their transversal sections are significant) and the rest are "thick", than one will neglect the last ones. Finally, one remains to verify if Vef is smaller or equal with Vrequired (cf. National Earthquake Codes).

Of course, don't look the general stability and maximum displacement verifications. Individual verifications need be done for each rigid body fragment, if its couplings with other vertical corps are very weakened. This is the special case of many masonry buildings with cracked vaults and arches; their fractures delimitate the "single" wall columns or piers. A similar case is the wall building with "slipping" wood beams (on the bearings); consequently, the behaviour factor k2 will be equal with about zero, in this situation.

We can name as "friction method" the proposed procedure for residual shear base evaluation. Although this approach is simple, it can be efficient. The use of the FEM (Finite Element Method) programs has some limits: a. the acceptation of the Theory of Elasticity for discontinue medium and for tension stresses (incorrect); b. the neglecting of the friction "connections" (underrating). Other programs, based on the Distinct Element Method, correct these inadvertences, but is too complicated for usual low high masonry buildings. The advantage of the friction method consists in these main aspects.

CONCLUSIONS

All aspects relieved here lead to the following main conclusions:

1. Old masonry structures are non-continuous solid systems, in the most cases. The computing procedures of the Mechanics (for usual continuum solids/structures) are inadequate for such fragmented systems. The Multibody Rigid and Elasto-Plastic Mechanics are the best theory for the structures with "distinct" components, (fragmented system).

2. The mechanical properties of the old masonry are very varied for the same structure. The selection of the representative values of seismic risk analysis means a major question for experts. Consequently, experimental tests are needed. There are preferred non-destructive in situ test measurements. Their number can be reduced, if we will select the most affected regions of the structural members. If a database exists, one can be accepted the use of their medium "residual" ultimate stress values for common buildings, also.

3. However, an approximate base shear assessment can be done using the proposed approach, based on the friction effect in the dynamic range. The found friction function can offer the needed accuracy in such safety risk evaluations.

4. For complex structures, having significant dimensions, one is recommended the use of a computer program based on the DEM. The programs based on the FEM can be used also, but it need introduce the effective existent separation lines in the real masonry structures.

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