A simplified procedure for the evaluation of the energy dissipation in out of plane mechanisms of masonry building

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SUMMARY:
The response of traditional masonry buildings that are stressed by out of plane seismic movements is still nowadays one of the most debated problems in the field of seismic engineering. The limit analysis of the equilibrium is the most used method to analyse this response due to its simplicity and the possibility to immediately evaluate the results. Notwithstanding, the traditional model does not allow to consider any dissipation of energy. In order to introduce a form of energy dissipation, the friction strengths developed by kinematic mechanisms have been included in the model. By the analysis of several types of kinematic mechanisms and comparing the consequent results to the ones got from a traditional modelling, it has been possible to evaluate the importance of the stabilizing effect of friction in the mechanism and to establish amplification factors to be applied to the limit analysis in order to consider on a lump sum basis the dissipation caused by friction.

Keywords: masonry, local mechanisms, limit analysis, energy dissipation.

1. INTRODUCTION

The studies of these last years and the observation of the damage scenery shown in the historical centres affected by the earthquake have demonstrated that the damages on traditional buildings are mainly caused by the activation of local damage mechanisms, which are connected to orthogonal actions on the medium plane of the panel boards. Analogously with the global behaviour of masonry buildings, the analyses concerning local mechanisms can follow both static and dynamic methods. Static methods lead to approximate results, but they are easier to be used; on the contrary, dynamic methods show more accurate results, but they can be harder from the calculation point of view. The use of powerful computers allow to profit by dynamic analyses even on a large scale; nonetheless, the complexity of these analyses make the following results hard to be checked. The damage phenomena connected with out of plane actions can be so many and so different one from another that they can be hardly automatized without the participation of an operator; for this reason, the necessity to provide an instrument for the evaluation of the out of plane vulnerability which can be applied on a large scale lead to prefer simplified methods, due to their easiness to be used. In particular, the limit analysis with a kinematic approach is the most used, in spite of the following limits:

- impossibility to consider the energy dissipation;
- impossibility to note the capacity reserve that occurs after the appearance of the cracks, because of rocking. This capacity reserve has been known through sperimental tests which are present in literature and it can be noted just by an approach to the displacements.

Because of the above mentioned reasons, often the limit analysis method provides precautionary results. The Italian Code consider all the above mentioned factors, and two approaches are proposed; both of them are based on the limit analysis: the first one is called linear kinematic analysis and it is a classical approach based on accelerations. The second one – which is called not-linear kinematic analysis – is based on displacements and it is aimed to evaluate the capacity reserve of the wall after the appearance of cracks. In addition to the initial system configuration, the procedure provides for considering other varied configurations up to the actual collapse configuration. Notwithstanding, during this process you miss the simplicity of the application and the possibility of a direct control that represented the most important advantage of the classical method. The aim of this study is to propose an alternative methodology that can lead to accurate results, maintaining the original simplicity of the limit analysis as well. During the first stage of our work, the study of the plasticity theory in the presence of friction and the evaluation of the friction strengths in the main kinematic mechanisms have allowed to consider the energy dissipation, which otherwise would have been disregarded by the model. During the second stage, several numerical analyses have been effected on different classes of kinematic mechanisms, varying the parameters which consider the construction details and taking into consideration the different friction levels. Acting in this way, it has been possible to evaluate the variability of the results due to the energy dissipation. In the third stage, these analyses have contributed to the definition of amplifying factors which allow to consider friction in a lump-sum way, without any need to directly evaluate the friction strengths each time. Finally, these amplifying factors have been applied to some examples, after having evaluated the friction coefficient by horizontal sliding tests, which have been effected using hydraulic jacks. The results have been compared to those provided by the analyses which were proposed by the regulations, and what has emerged is that the evaluation of the friction strengths that has been got directly or through the use of amplifying factors can represent a reliable alternative to the not-linear kinematic analysis.

2. THE METHOD OF THE LIMIT ANALYSIS IN THE PRESENCE OF FRICTION: APPLICABILITY CONDITIONS.

Despite the fact that masonry is a material which is not resistant to the tensile strengths and consequently a dissipation due to plastic moment in the hinges can not be assumed, it is still possible to consider that a certain quantity of energy is dissipated because of the friction strengths that get active along the cracks during the mechanisms.
Notwithstanding, the presence of friction involves some difficulties that are connected with:
Uncertainty about the effective use of the limit analyses results;
Uncertainty about the evaluation of the friction strength along the cracks.
The first kind of uncertainty is connected with the definition of a elasticity domain and a law that determines the plastic sliding in the presence of friction. In fact, the limit analysis theorems are classically formulated considering the associated bond hypothesis, which can be analytically formulated only provided that the following factors are satisfied:
Definition of a convex instantaneous elastic domain that can identify the potentially plasticizable stress states;
Definition of a sliding associated law which rules the plastic deformation increments that are normal at the yielding surface.
The convex domain is defined in space assuming that one or more plasticity functions are not-positive (Eq. 1) under the conformity conditions (Eq.2):

$$\varphi_\alpha(\sigma_{ij}, x) \leq 0 \qquad \alpha = 1,...Y \tag{1}$$

$$\varphi_\alpha \leq 0 \qquad \dot{\lambda}_\alpha \geq 0 \qquad \varphi_\alpha \dot{\lambda}_\alpha = \dot{\varphi}_\alpha \dot{\lambda}_\alpha = 0 \tag{2}$$

Here x represents the inner variables which control the modifications in the domain induced by the previous plasticizing; the plastic normality law is defined by the gradient of the function φ_α:

$$\dot{\varepsilon}_{ij}^{P} = \sum_{\alpha=1}^{Y} \frac{\partial \varphi_\alpha}{\partial \sigma_{ij}} \cdot \dot{\lambda}_\alpha \tag{3}$$

The Eq.3 is defined as associated law or normality law of the plastic sliding, since it indicates the direction of the plastic sliding associated to a certain stress states on the yielding surface; it will be perpendicular to the tangent straight line which passes through that point of the surface. The associated bond results from a mechanical hypothesis known as Drucker's law, which develops through the following inequalities:

$$\left(\sigma_{ij} - \sigma^*_{ij}\right)\dot{\varepsilon}^P_{ij} \geq 0 \qquad \forall \sigma^*_{ij} \quad \text{so that} \quad \varphi\left(\sigma^*_{ij}\right) \leq 0 \tag{4}$$

Here the quantities without asterisk are associated together through the constitutive bond and σ*ij is any plastically admissible stress state, or rather the one which is within or on the limit of the yielding surface. It can be demonstrated that the hypotheses of the associated bond or rather normality and convexity derivate from Eq.4; if only one of these hypotheses is broken, the law is not valid anymore and the bond can not be defined as associated. The entire plasticity theory is formulated for the associated bond. In fact, the static and kinematic theorems and the oneness of the solution can be demostrated starting from the Drucker's law: all the kinematic multipliers are higher than the real collapse multiplier, whereas the static multipliers are lower. The solution is only one and the real collapse multiplier is the one that is statically admissible and kinematically sufficient. Anyway, it is important to underline that the Drucker's law must not to be considered as a law of nature that has to be necessarily satisfied; in fact, it is the definition of a particular category of behaviours. In particular, the associated bond is not suitable to describe realistically the response of a material if this response is greatly influenced by the pressure, as it happens in the presence of friction. In fact, it is possible to demonstrate that, when the yielding function depends on two variables (for instance, the Coulomb's domain), a normality law of the plastic sliding starting from the yielding fiunction can not be defined. The plastic sliding will happen perpendicularly on another function, g(T,N)=T, which defines the plastic potential. Therefore, returning to the general case, we can state that a bond can be defined as "associated", when the yielding function is simultaneously the plastic potential function too; if this is the case, the material will be defined as "standard". (Radenkovìc 1961). On the contrary, when it is necessary to define two different functions for the yielding surface and the plastic potential, it is a not-associated bond and the material will be not-standard. Going back to the initial problem, the goal was to verify a correct application of the limit analysis in the presence of friction. The mechanical problem can be considered as a problem of friction contact between rigid blocks which is regulated by the Coulomb's law. The yielding domain in the space of the two shear stresses, τ1 and τ2, and the normal stress σ is represented by the Coulomb's cone. Given these conditions, the law of plastic normality is broken and consequently one of the fundamental hypotheses of the associated bond is missing. Basically, it means that the classical theorems of the limit analysis do not guarantee the oneness of the solution concerning the collapse multiplier, therefore there will be a range of solutions that will be both statically admissible and kinematically sufficient. It remains to verify whether there are any particular conditions which guarantee the validity of the cracking calculation theorem anyway, in spite of the presence of friction. In the particular case in which the normal stress is a locally determined quantity, the Coulomb's cone can be represented on the plane of the shear stresses τ1 and τ2; in this case, it will be reduced to a circle with the centre in A, extreme of the vector of the normal stress. The behaviour of the material does not depend on the variation of the normal stress anymore, since it is considered as constant quantity. Given this condition, the Drucker's law is always satisfied, the normality law is always respected and the study of the behaviour of the material can be compared to the study of a rigid-plastic material which is characterized by a constant limit shear stress:

$$\left(\tau - \tau^*\right)\dot{\varepsilon}^P_{ij} \geq 0 \tag{5}$$

$$\tau = \sigma \tan\phi \tag{6}$$

here ϕ represents the friction angle. In these conditions, the possibility to use the theoretical instrumentation that is effective for the associated bonds is guaranteed.

2. EVALUATION OF THE COLLAPSE MULTIPLIER IN THE PRESENCE OF FRICTION

2.1. Base hypothesis, and calculation parameters

Facing the study about the sensitivity of the collapse multiplier to friction, three fundamental hypotheses have been formulated:

- the friction has been evaluated using a Coulomb's domain with constant normal stress on the cracks, according to the reasons which have been discussed in the previous chapter;
- the cracks will be activated along the joints between the blocks, following the joints between the stones; therefore, their inclination will depend on the dimensions of the blocks themselves. As example, we have considered masonries with rigid and regular blocks;
- since the friction depends on the masonry's weight on the crack, the displacement along the vertical joints – which do not suffer any pressure – does not create any strength; the friction happens just for the sliding along the horizontal joints, which suffer pressure indeed.

Considering the last hypothesis, you can deduce that there is not any friction in the mechanisms in which only the out of plane walls are involved; in fact, all the displacements of the points on the crack (which is highlighted in blue in figure 1*a*) are vertical. The types of kinematic mechanisms which cause the activation of friction strengths are the ones in which parts of the in-plane walls are involved. These kinds of kinematic mechanisms – which can be called *mixed mechanisms* – can be activated just by virtue of good interconnection between the wall crosses. In this case, the points that are on the cracks suffer both vertical and horizontal displacements (which are highlighted in red in figure 1*b*). A similar situation occurs in the case of walls with semi-connected, where you can observe friction just on the horizontal joints of the stones laid across the wall (fig.1*c*). The mixed mechanisms are very frequent in the damage sceneries of the historical centres and they can show countless configurations.

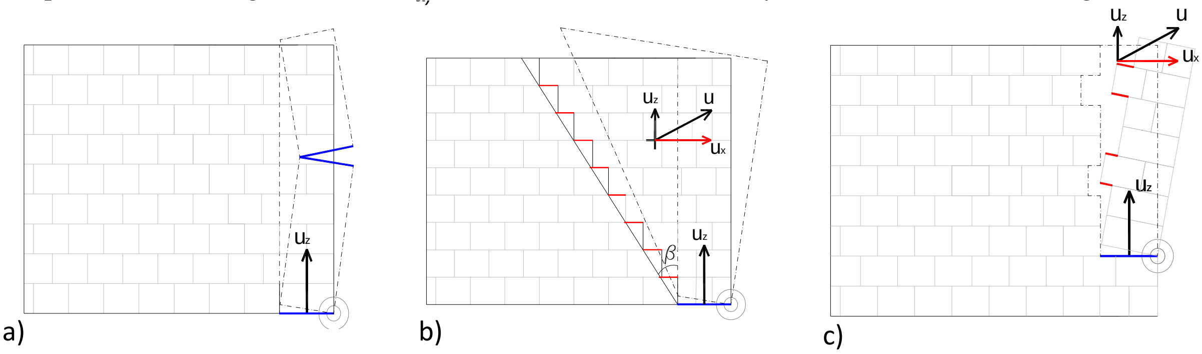

Figure.1. (a) Out of plane mechanism: there are not horizontal sliding and consequenly the friction strengths are avoid; (b) mixed mechanism: you can notice horizontal sliding along the joints, therefore friction strengths happen; (c) mechanism of a wall with semi-connection: there is friction only on the connection ashlars.

The figure 2*a* shows a summary of the analysed cases; the classification has been effected according to the position of the damage in the structure, according to the shape and design of the separation wedge and according to the connection degree. The parameters which have been used in the analysis were chosen in order to consider the three following factors (figure 2b):

- *Building typology:* it is considered through the ratio between the inter-axis L of the transverse walls and the height h of the involved out of plane wall. We have considered a range of values that are commonly observed in the traditional typologies, or rather $0{,}75 \le L/h \le 1{,}25$;
- *Texture of the masonry:* the dimensions of the blocks and consequently the inclination β of the crack depend on it; squat blocks correspond to small inclinations, while thin blocks correspond to bigger inclinations. The most frequently observed values have been considered, or rather those which correspond to the range $0 \le \beta \le 25°$. An inclination which is equal to $\beta = 0°$ lead us to the case of a simple wall overturning, in which the friction strengths do not provide any contribution.
- *Shape of the crack:* in the kinematic mechanisms that are characterized by parts of separation which are formed by several wedges, the ratio between the heights of the wedges themselves is

considered. We have considered the values included between $0{,}3 \leq h_1 / h_2 \leq 3$

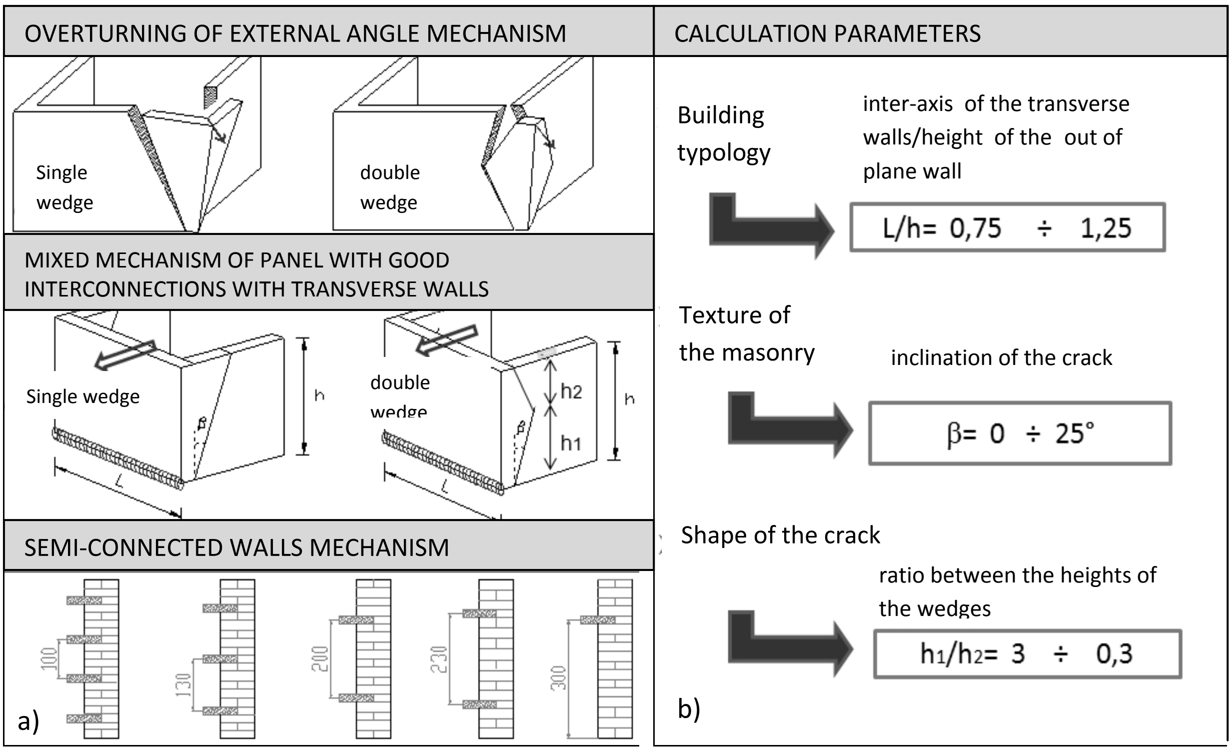

Figure.2. a) Classification of the analysed mechanisms; b) calculation parameters considered in the analyses.

3. RESULTS OF THE ANALYSES

For each kinematic mechanism, we created a diagram showing the running of the collapse multiplier in function of the inclination angle of the cracks and considering as fixed the values of the parameters which control the distance of the transverse walls (L/h) and the shape of the separation portion h_1/h_2); the operation has been repeated several times varying the parameters one by one, in order to get different curves and to be able to compare them. The figure 3 represents the running of the collapse multiplier α according to the variation of the angle of the crack, taking into consideration single wedge mechanisms (*a*) and double wedge mechanisms (*b*); in both case it is possible to notice how the gap between the two curves increases because of the effect of friction due to the increase of the angle β; this can be explained by the fact that the more the wedge weight increases the more the friction strength on the crack increases. On the contrary, the figure 3 *c* shows the case of the simple overturn of a wall with semi-connection; the light grey line indicates the values of the multiplier without considering the friction on the surfaces of the stones laid across the walls, which corresponds to ignoring the connection; on the other hand, the black line indicates the values obtained calculating the friction. The comparison shows that, considering the friction, it is possible to notice an increase of the collapse multiplier which is approximately equal to 20-25% for the walls that are connected to the transverse walls and even a more than 30% increase for the semi-connected walls.

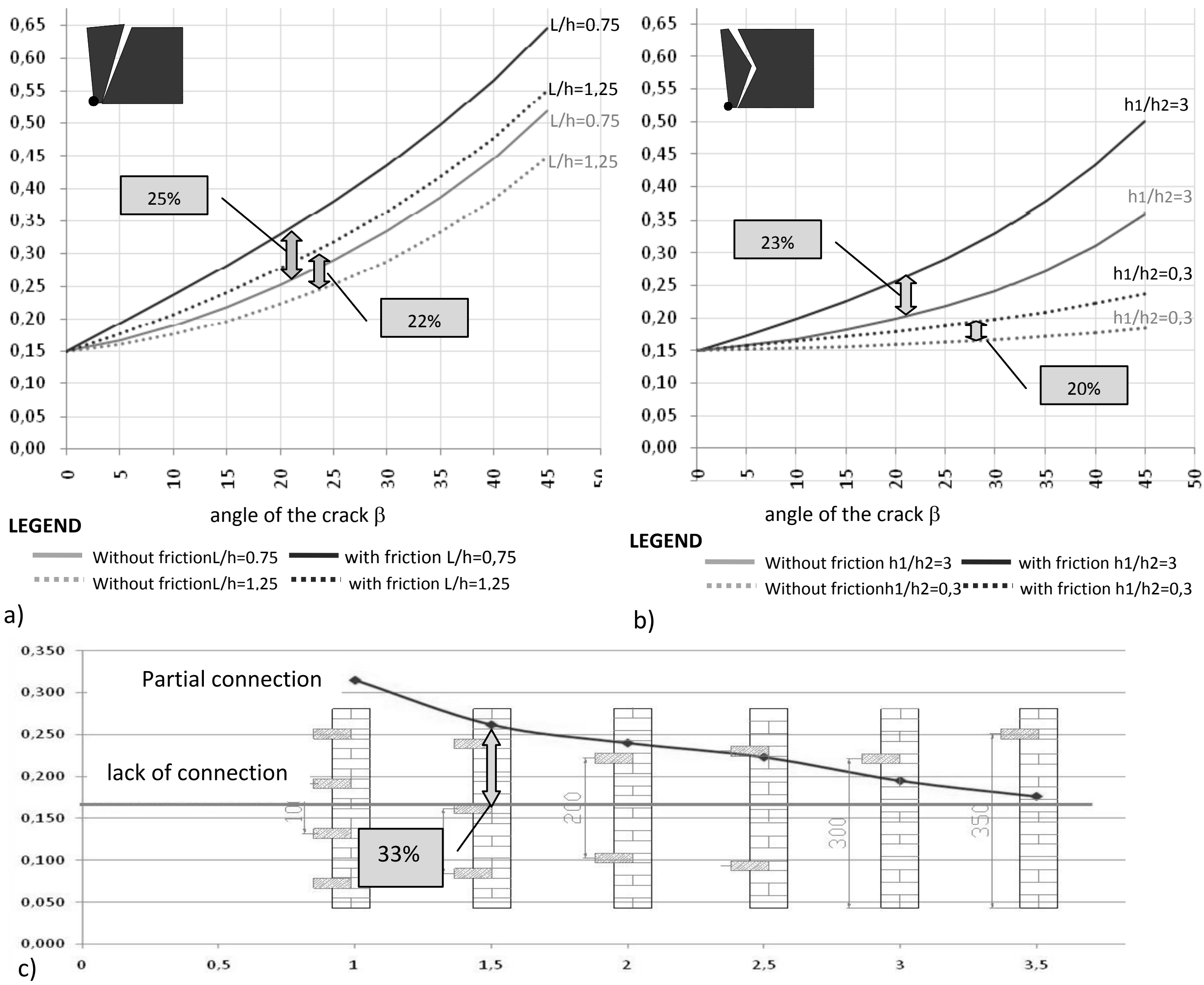

Figure 3. Running of the collapse multiplier for different kinematic mechanisms, changing the inclination β of the crack, and considering or not the friction: a) single wedge of wall connected to shear walls for different L/h; b) double wedge of wall connected to shear walls for L/h=1 and varying h_1/h_2; c) kinematic mechanism of wall with semi-connected varying the number of stones laid across the wall. The calculation considers the thickness of the wall stressed out of plane: s = 0,60m ;the thickness of the wall stressed in the plane: s_1 = 0,60m; the blocks specific weight:γ = 23,00 kN/mc; the friction coefficient:f = 0,45

The analyses have shown that the more the crack is inclined the higher the contribution of the friction strengths is; moreover, since this inclination depends on the dimension of the blocks, it is possible to conclude that the evaluation of the friction becomes important for thin blocks. Besides, the contribution of the friction increases in those building typologies characterized by close transverse walls (or rather with the increase of L/h). This aspect can be explained by the fact that in the typologies characterized by small inter-axis between the transverse walls, the contribution of the wall stressed out of plane is less important than the total contribution. In order to properly evaluate just the importance of the friction in the different kinematic mechanisms, its stabilizing contribution has been analysed separately and shown in the figure 4 as percentage. It is possible to notice that the mechanisms in which the friction is more important are those characterized by the overturn of an external angle of the building; in these cases, the contribution is higher than ¼ of the total contribution. In the single-wedge mechanisms, the contribution of the friction is just a few lower than ¼ of the total and about ½ of the contribution of the masses stressed in plane; on the other hand, in the double-wedge mechanisms, though the contribution of the friction strengths is about ¼ of the total, it evens up the contribution of masses stressed in plane. Finally, in the case of the overturning of semi-connected walls, it changes a lot according to the number of stones laid across the wall which have been considered. However, we can conclude that in all the mechanisms that have been analysed, to disregard the friction is an error which can be particularly heavy in some typologies of walls.

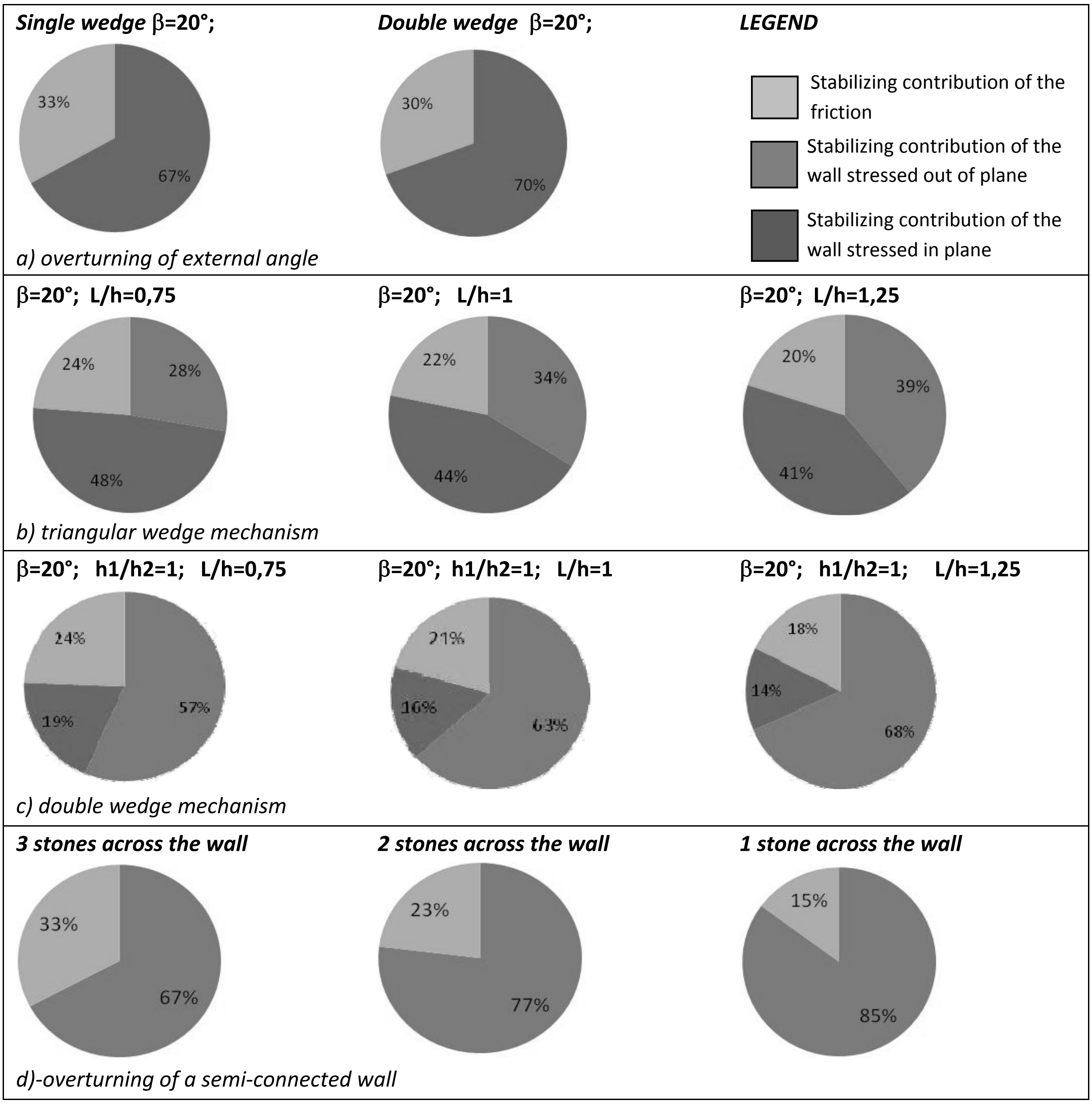

Figura 4. the stabilizing contribution of the friction towards the total. Comparison of different mixed kinematic mechanism.

4. DETERMINATION OF CORRECTIVE COEFFICIENT FOR THE EVALUATION OF THE ENERGY DISSIPATION DUE TO FRICTION.

The analyses of the parameters have shown that defining the vulnerability of historical buildings to out of plane stresses, the role of friction can not be disregarded. Notwithstanding, the definition of the working of the friction strengths can be difficult; for this reason, in order to provide a rapid and professionally valid instrument, some minimal coefficients have been prepared to increase the results of the analyses, which allows to consider the friction strengths in a lump-sum way. These coefficients have been determined according to the analyses and they are the result of the ratio between the collapse multiplier obtained from the model that considers the friction and the collapse multiplier of the traditional model (Eq.7):

$$C_\mu = \frac{\alpha_\mu}{\alpha} \quad (7)$$

C_μ is the increase coefficient for friction;
α_μ is the collapse multiplier of the model that considers friction;
α is the collapse multiplier calculated disregarding friction;
Therefore, repeating the analyses according to the change of the parameters which have been considered in the previous chapters, it has been possible to establish increases for friction not just concerning different kinematic mechanisms, but also considering different texture of the masonry, building typologies and damage geometry. Moreover, the increases have been got for different values of the wall-wall friction coefficient (Tab.1). Then, after having assumed the most probable damage typology and knowing the features of the analysed masonry, it is possible to determine the increase for friction in a lump-sum way. In order to exceed the border of a specific case and to make the coefficients usable in a general way, some ranges of friction coefficients which are frequent in historical masonries have been determined. Within each range and for each mechanism, it is possible to choose the coefficient according to the inclination of the supposed or observed crack. It is also important to underline that the coefficients shown in the table are the lowest coefficients and, for this reason, they indicate in a precautionary way the lower limit for the relative class. It is also possible to find further increases, provided the presence of improving situations, such as the presence of close transverse walls (inter-axis L/h<1), or a particularly stabilizing shape of the separation wedge (double wedge with h1/h2<0,33). The following tables show the values of the coefficient C_μ for the different classes of kinematic mechanisms:

Table 1. Corrective coefficients for mixed mechanisms of single-wedge walls

Friction coeffic.	Crack inclination				Increase for L/h<1
	β=5°	β=10°	β=15°	β=20°	
μ ≤0,4	1,13	1,21	1,26	1,28	1,05
μ =0,5	1,16	1,26	1,32	1,35	1,05
μ =0,6	1,19	1,30	1,38	1,41	1,05
μ>0,7	1,23	1,37	1,45	1,49	1,05

Table 2 . Corrective coefficients for mixed mechanisms of double-wedge walls

Friction coeffic.	Crack inclination				Increase for L/h<1	Increase for h1/h2≤0,3
	β=5°	β=10°	β=15°	β=20°		
μ <0,4	1,07–	1,14	1,20	1,25	1,05	1,05
μ =0,5	1,09	1,18	1,25	1,32	1,05	1,05
μ =0,6	1,11	1,21	1,30	1,38	1,05	1,05
μ >0,7	1,12	1,24	1,35	1,45	1,05	1,05

Table 3. - Corrective coefficients for the overturning of the single-wedge external angle

Friction coeff.	Crack inclination				Increase for L/h<1
	β=5°	β=10°	β=15°	β=20°	
μ ≤0,4	-	1,41	1,44	1,52	1,05
μ =0,5	-	1,54	1,65	1,70	1,05
μ =0,6	-	1,65	1,75	1,84	1,05
μ>0,7	-	1,68	1,78	1,88	1,05

Table 4. – Corrective coefficients for semi-toothed walls

Friction coeff.	Crack inclination		
	1stone for each m	1,5 stone for each m	2 stones each m
μ <0,4	1,3	1,45	1,6
μ =0,5	1,37	1,60	1,75
μ =0,6	1,45	1,73	1,8
μ >0,7	1,52	1,82	1,85

5. EVALUATION OF THE OUT OF PLANE VULNERABILITY USING THE CORRECTIVE COEFFICIENTS DUE TO FRICTION: TWO CASES.

The procedure for the evaluation of the seismic vulnerability of walls that are stressed out of plane by the use of corrective coefficients for friction can be shown by two real cases: the former monastery of S. Giuliano and a Primary School in Catania. In the first case, the expected kinematic mechanism was already known on the grounds of the observation of the crack setting in progress; in the second case, lacking a clear crack setting, an hypothesis has been made starting from the observation of the masonry weaving and the building features.

The former monastery of S. Giuliano is a monumental building, which is placed in the historical centre of Catania and has a great historical and artistic value. The building shows a clearly visible crack and deformation setting caused by the succession of the historical earthquakes, especially in the most ancient part. The developed activities have been meant to evaluate the seismic danger and the consequent safety installation. In particular, what has emerged is the presence of an already activated kinematic mechanism concerning a wall with a ground hinge and well-connected to the shear walls. In fact, these shear walls show heavy passing cracks which delimit double-wedge shaped separation parts, as shown in figure 5.

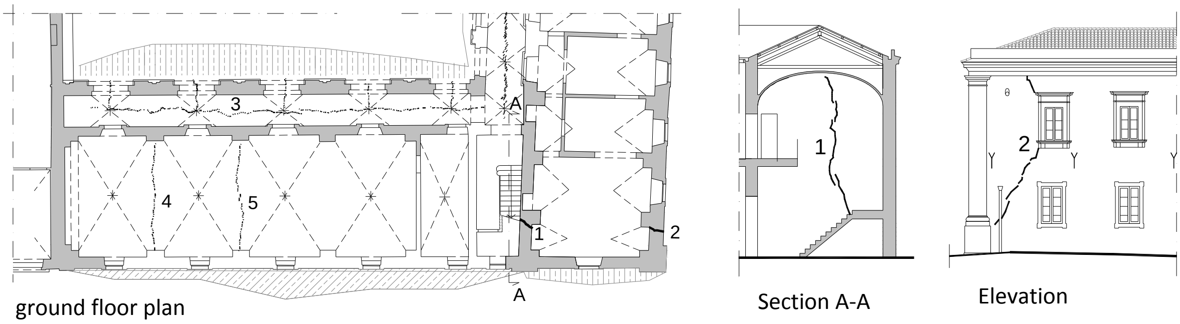

Figure.5. Monastery of S. Giuliano a Catania, survey of the crack and deformation setting.

The analyses effected on the scene have also allowed to calculate an estimation of the wall-wall friction coefficient by the use of two horizontal sliding tests with hydraulic jacks. These tests have provided the opportunity to evaluate the ultimate shearing strength of two walls, which belong to the same typology but are concerned by different values of the normal stress. Therefore, establishing a connection between the strengths that have been surveyed in this way – with the relative normal stress values, which have been measured by traditional tests with flat jack, it has been possible to obtain the shearing strengths without normal stress or masonry cohesion, and the friction coefficient, estimated at μ =0,83. In accordance with these data, it has been possible to effect those analyses which were aimed to the evaluation of the vulnerability of the wall panel taken into consideration and to the dimensioning of a possible constraining system meant to prevent the kinematic mechanism.

The second case of study it does not show any particular historical or artistic quality. Nonetheless, it has an important function, since it accomodates a primary school. Also in this case, some analyses have been effected to know the building features and the parameters of the materials, in order to get a realistic model for the evaluation of the seismic risk. The building technique is the one that is typical of the middle of the last century, and it is characterized by the presence of masonry vertical structures and concrete slabs. The roof is formed by a wooden structure with roof trusses which is placed upon a reinforced concrete roof band, connected to the walls below only by friction. Floor band and lintel band have been surveyed too. The survey of the crack setting has not shown clear damages, whereas the analyses of the wall parameters have shown a regular weaving, which is composed by squared lava blocks, and good connection between the wall crosses. Due to the lack of an active crack setting, an hypothesis about the possible post-seismic damage mechanisms have been formulated on the grounds of the data concerning the technique and the building details. In fact, the presence of the mixed technique with the concrete slabs has allowed us to immediately reject the possibility of a wall rigid overturning of the below panels. On the other hand, the top of the building is not constrained enough, in fact, the connection by friction to the concrete roof band – on which just the roof weighs – is not sufficient to prevent the overturning of the top wall (fig.7).

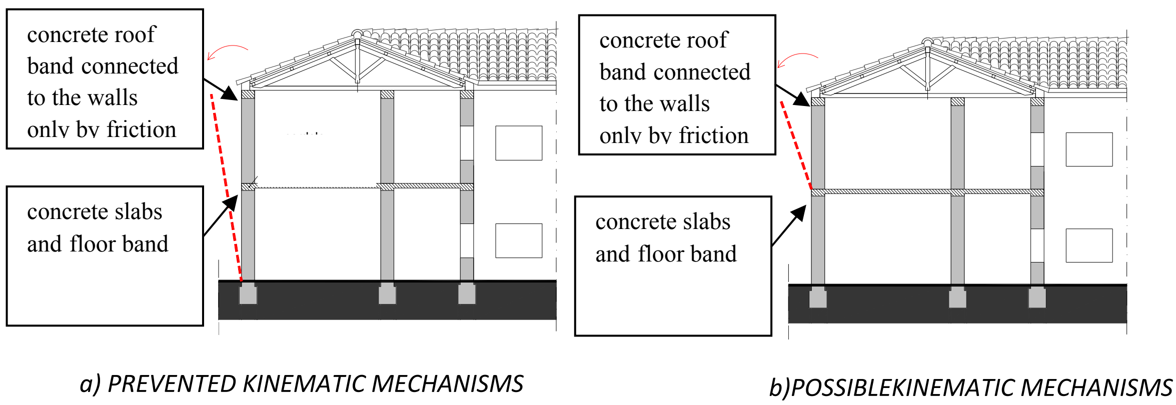

Figure 7. Identification of the possible kinematic mechanisms in accordance to the considerations about the building system: *a)* the floor band prevents the overturning of the wall below; *b)* the roof band which is connected by friction does not provide a sufficient constraint to the overturning of the top part.

Once the most vulnerable (from the point of view of the constraints) wall portion has been detected, it has been possible to express some hypotheses about the probable geometrical configuration of the kinematic movement. The presence of good connections – which have been surveyed during the research – makes us favourable to the formation of a mixed mechanism with the dragging of triangular portions of wall. The regular texture of the wall (composed by medium and large squared lava blocks that have a quite stretched shape) allows to suppose the formation of a crack which is inclined by at least 15° on the orthogonal shear wall; in fact, it is likely that the crack forms along the joints between the blocks, rather than through the blocks themselves. Finally the horizontal sliding tests have allowed to obtain the wall-wall friction coefficient estimated at μ =0,75. In accordance with these data and the relative hypothesis, the analyses have been effected on a wall, in order to evaluate the seismic risk for out of plane stresses and to define a possible intervention. However, it is important to underline that, during the analyses on the wall, the connection by friction between masonry and roof band has been included, considering a wall-band coefficient that is equal to μ 0,45.

6. RESULTS AND CONCLUSIONS.

The damage mechanisms shown in the previous chapter have been surveyed using different methods of analyses, in order to compare the results. The methods of analyses considered are listed here below:

- Linear kinematic analysis in accordance to the D.M.14.01.2008;
- Linear kinematic analysis with simplified evaluation of the friction strengths through the corrective coefficients C_μ;
- Linear kinematic analysis with direct evaluation of the friction strengths;
- Not-linear kinematic analysis in accordance to the D.M.14.01.2008;

In all the analyses, the level of vulnerability is obtained comparing the seismic demand of the site and the system capacity: in the linear kinematic analyses this comparison is effected in terms of accelerations; in the not-linear analyses, it is effected in terms of displacements. Anyway, it is necessary to evaluate the seismic danger of the site, considering the parameters that determine the spectrum shapes: ground acceleration a_g; maximum amplification factor of the spectrum in horizontal acceleration F_0; beginning period of the constant velocity portion of the spectrum T^*_C; ground factor S. Moreover, the level of vulnerability is function of the ratio *Z/H* – or rather the centre of gravity of the kinematic mechanism towards the total height of the building –, of the first period of the structure T_1 and of the secant period T_s – or rather the fundamental period of the structure that is calculated in correspondence with the limit situation of conventional collapse. Table 5 shows the mentioned parameters for the two cases:

Table 5. Calculation parameters used during the analyses

	Parameters which define the shape of the spectrum				Wall parameters		
	a_g	F_0	T^*_C	S	T_1	T_s	*Z/H*
Case I: Former	0,204	2,43	0,353	1,44	0,29	3,02	1
Case II: Primary school	0,216	2,47	0.390	1,13	0,14	2,13	0,75

Tables 6 e 7 shows the results concerning the two cases:

Table 6. FORMER MONASTERY OF S.GIULIANO, mixed mechanism around the base, single-wedge.

	capacity	demand	Work rate(%)	PGA (a_g)
a. lin.NTC	0,151	0,147	97	0,210
a.lin. coeff. C_μ.	0,236	0,147	62	0,330
a. lin. attrito	0,285	0,147	51	0,400
a. non lin.NTC	0,761	0,209	27	0,755

Table 7. II° CIRCOLO DIDATTICO SCHOOL, mixed mechanism around the first floor, single-wedge

	capacity	demand	Work rate (%)	PGA (a_g)
a. lin.NTC	0,161	0,312	193	0,112
a.lin. coeff. C_μ.	0,240	0,312	130	0,166
a. lin. attrito	0,256	0,312	122	0,177
a. non lin.NTC	0,407	1,056	385	0,056

Observing the results concerning the case I (tab. 6), which is characterized by a ground kinematic mechanism, it can be noticed that the linear kinematic analysis – as it is proposed by the Italian Code – is rather preserving, while the not-linear analysis is prejudicial to safety. The analyses that consider the friction are in an intermediate position. The results concerning the case II – where the kinematic movement occurs around the first level of the builiding – lead to a totally opposite situation (tab.7). In this case, the more preserving results derive from the not-linear analyses; the analyses that consider the friction are prejudicial to safety, while the linear analysis is in an intermediate situation. Notwithstanding, the demand amplification observed in the not-linear analysis (which derives form the filter-effect of the structure on the wall that is object of the overturning) seems to be too penalizing: in fact, the collapse mechanism should be activated with a ground acceleration that should be equal to a_g=0,056. On the other hand, this result is denied by the evidence of the events, since, despite the fact that this building was built in an area that is characterized by a frequent seismic activity – and, consequently, it has surely been object of seismic movements during its life –, it does not show any particularly evident crack setting. In conclusion, it is possible to state that, in case of ground mechanisms, the analyses which consider directly or indirectly the friction through the coefficients C_μ can always represent a valid alternative to the not-linear analysis, since they provide more verifiable results, assuring safety as well. This possibility of an immediate control by the operator represent a great advantage, because it reduces to the least the possibility of making a mistake. Finally, concerning the mechanisms that are located at the top of the buildings, the analyses that evaluate the friction may lead to results that are more prejudicial to safety than the ones got by the not-linear analysis; for this reason, the use of the methodology for the evaluation of the friction applied to top wall kinematic mechanisms must be valued case by case.

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