Assessment of Masonry Buildings Subjected to Landslide-Induced Settlements: From Load Path Method to Evolutionary Optimization Method

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Abstract. One of the main difficulties, when dealing with landslide structural vulnerability, is the diagnosis of the causes of crack patterns. This is also due to the excessive complexity of models based on classical structural mechanics that makes them inappropriate especially when there is the necessity to perform a rapid vulnerability assessment at the territorial scale. This is why, a new approach, based on a ‘simple model’ (i.e. the Load Path Method, LPM), has been proposed by Palmisano and Elia for the interpretation of the behaviour of masonry buildings subjected to landslide-induced settlements. However, the LPM is very useful for rapidly finding the ‘most plausible solution’ instead of the exact solution. To find the solution, optimization algorithms are necessary. In this scenario, this article aims to show how the Bi-directional Evolutionary Structural Optimization method by Huang and Xie, can be very useful to optimize the strut-and-tie models obtained by using the Load Path Method.

1. Introduction

The Strut-and-Tie Model (STM hereafter) was originally developed by Ritter [1] for the analysis and design of reinforced concrete beams under shear. Schlaich et al. [2] proposed a global approach to the structural design by means of STM. The Strut-and-Tie Model implies that the structure is designed according to the lower bound theorem of plasticity [2].

It is often not necessary a deep knowledge of the Strut-and-Tie method to find truss models that best fit the regions under study. This is also due to the fact that often it is possible to adapt well known pre-solved examples to the specific case under study.

In non-standard cases the development of the 'optimum' truss model can require not only an expert designer but also it can be extremely time consuming. This is the reason why many procedures (e.g. the Load Path Method, optimization criteria), that aim to find the most 'accurate' solution with the minimum 'effort', have been proposed in the last decades [3].

According to Roca et al. [4], simple methods based on fundamental principles, such as the limit theorems of plasticity, are valuable because they provide easy and accessible understanding on fundamental aspects of the structural response. For this purpose, they need to show reasonable simplicity while affording the description of the essential phenomena governing the structural behaviour.
Following the approach by Roca et al. [4], which is relevant to shear walls, Palmisano and Elia [5] have discussed the results of a study on the use of the Load Path Method to interpret the behaviour of masonry buildings subjected to foundation settlements due to landslide.

The approach proposed by Palmisano and Elia [5], differently from that of Roca et al. [4], aims to predict the structural behaviour on the basis of both equilibrium models and consistency. Conversely, differently from what proposed by Roca et al. [4], the proposed approach is not aimed to quantify the ultimate capacity of masonry walls in the above mentioned conditions, but it intends to show the effectiveness of simple models for the prediction of structural behaviour as well as for the diagnosis of the crack patterns.

The proposed approach starts from the consideration that a structure, during its life, undergoes several 'evolutions' [6]. The whole process can be brought back to the sequence of a limited number of instantaneous 'configurations' (i.e 'States'), each one caused by a specific 'State Transformation'. Structural behaviour analysis can be reduced to the verification of those configurations and of the relevant transformations.

If dealing with masonry structure the following states can be defined:

- **State 0**: the structure is not stressed.
- **State 1**: the structure is stressed but there are not cracks.
- **State 2**: first cracks appear.
- **State 2a**: cracks become larger and new cracks appear (i.e. crack evolution state).
- **State 3**: ultimate limit state. The structure is heavily damaged with no residual strength and stiffness (i.e. the structure is not capable of sustaining further loads).

So far and in this article, the proposed approach has been applied only for material linear behaviour and without including tensile resistance limits. This means that the results discussed in this article are valid only up to the above-mentioned state 2. To understand what happens in states 2a and 3, it is necessary, at least, to include fragile tensile response in the models. As stated in the conclusions, this is the subject of an on-going research that will be published in future articles. However, the proposed approach has general validity. The above-mentioned limitations have only influence on the results so far obtained.

Moreover, it is worth noting that, by using the proposed approach with the above-mentioned limitations, it is immediately possible to understand the cause of first cracking in a masonry wall. This is an important result because in many cases, taking to account the tensile fragile response of masonry, first cracking can cause the failure of the element.

According to [5] the LPM is very useful for finding the 'most plausible solution' instead of the exact solution. The 'most plausible solution' is the path to which, among different equilibrated load paths, is associated the lowest value of the total strain energy. This approach can be carried out by very simple mathematical methods and, in many cases, seems to be very useful because it is able to immediately catch the 'dominant path' (i.e. the one followed by the majority of the total load) in order to highlight immediately and easily, the failure mechanism and the relevant crack pattern.

To find the solution (i.e. the unique path that respects the equilibrium conditions and, at the same time, minimises the total strain energy of the structural system) optimization algorithms are necessary.

Following this approach this article aims to show how the Bi-directional Evolutionary Structural Optimization method [7] can be very useful to optimize the strut-and-tie models obtained by using the LPM in masonry buildings subjected to landslide-induced settlements.

In fact, the assessment of landslide risk is a research topic of increasing interest all over the world due to both an increasing awareness of the dramatically important impact of landslides on the socio-economic environment and an increasing request for development and extension of urbanisation in areas prone to landsliding ([8-15]). In Italy this problem is particularly relevant in the areas located in the southern Apennines, where landsliding is widespread and responsible for frequent damages to structures and infrastructures.
2. Analysis of the behaviour of a masonry panel subjected to foundation settlements by using the LPM

In a LPM approach, Palmisano and Elia [5] have proposed some models for understanding the brick-mortar interface behaviour as well as the global one.

In this paragraph, some macro-models proposed by Palmisano and Elia [5] are reported. These models, obtained by using the Load Path Method, aim to interpret the structural behaviour of a masonry wall subjected to foundation settlements due to landslide.

The following assumptions have to be made:
- settlement is only due to the landslide movement; it does not depend on the loads acting on the masonry wall;
- masses are concentrated;
- the masonry wall is infinitely stiff respect to the foundation soil;
- a perfectly plastic constitutive law at the ultimate limit state has been hypothesised for the soil.

These assumptions have been made only to ‘draw’ some typical examples and to make the reader familiar with the use LPM in this scenario.

Despite the assumptions of the case study, that benefit the simplicity of the analysis, the method has general validity.

Figure 1a [16] shows the structure at the state 1 (static equilibrium before the soil settlement). In this state, because of the simplicity of the model, there are only descending loads and, in this macro-model, there are no deviations of the travelling loads. Actually, a microscopic analysis would show that travelling loads have to deviate in order to cross the brick-mortar interface [17].

In figures 1b-e ([16], [17]), four different and possible (i.e. in equilibrium) load paths at the state 2 (after soil settlement), for the case of a settlement that involves the lateral part of a masonry wall ('lateral settlement' hereafter), are represented (i.e. 'hogging' condition). The settlement has been modelled as a complete loss of contact between the soil and the right bottom side of the masonry wall.

Such loss of contact at the soil-wall interface causes the interruption of some load paths of the state 1, the relevant modification of the interrupted paths and the modification of other paths to restore global equilibrium. It is worth noting that, differently from what shown in figures 1b-e, the components $F_i$ should divide themselves into parts which should follow different paths to minimise the total strain energy of the system.

Nonetheless, a simplified sketch, representing the whole load which follows a chosen shape of path, has been reported in the figures. Such assumption seems in fact to be very useful for immediately catching the 'dominant path' (i.e. the one followed by a large part of the total load) to enlighten the failure mechanism and the relevant crack pattern.

It could seem strange that an unsymmetrical settlement produces a symmetrical response of the wall. Actually, in the cases under study, thanks to the last two above-listed assumptions and to the uniform load, the structural response should be symmetrical and hence the load path should be symmetrical even though the settlement involves only one side of the panel. Obviously, these results are only the consequence of the above-mentioned assumptions. This is why, when dealing with real cases, stiffness differences in the wall, relative stiffness between soil and wall, non-perfectly plastic response of the soil, cause, even for uniform acting load, an unsymmetrical behaviour with concentration of deviating load paths in the area just near settlement. However, the proposed approach remains valid. Firstly, because the proposed procedure is general, i.e. it is capable to solve both symmetrical and unsymmetrical cases. Secondly because, even in an unsymmetrical response, the shape of the load path, in the part of the wall subjected to settlement, is not different from that of symmetrical response. This means that the shape of the crack pattern, in the part of the wall subjected to settlement is the same.

Models in figures 1b-e make easily catch the effects of the soil settlement on the structure:
- because of equilibrium conditions, soil pressure diagram in state 2 is different from that of state 1; moreover, because of the adopted assumptions, soil pressure is nil on an area symmetrical to the one that has undergone the settlement;
- paths in tension arise in the masonry wall;
- load deviations generate thrusts that can find equilibrium by paths in tension and in compression.

Figure 1. Settlement that involves the lateral part of a masonry wall. State 1 (a), State 2 Load Path LP(1) (b), State 2 Load Path LP(2) (c), State 2 Load Path LP(3) (d), State 2 Load Path LP(4) (e), State 2 Load Path LP(5) (f)

Regarding the micro-models referred to the brick-mortar interface when crossed by tension fluxes see [16].

From the visual analysis of the paths in figures 1b-e, it can be deduced that combining the LP(1) with LP(3) there should be a saving in the strain energy, with respect to the shown paths, due to the absence of a thrust path in the middle of the panel. Hence it is possible to introduce a new load path (LP(5); Fig. 1f [16]) in which half of the load follows LP(1) and the other half follows with LP(3).

In figures 1b-f possible (i.e. in equilibrium) load paths for the cases of lateral settlement are shown.

As above discussed, only one path respects the equilibrium conditions and, at the same time, minimises the total strain energy of the structural system. The solution (i.e. the identification of this path) can be found either by FEM analysis or by optimisation algorithms (e.g. [3]). There are many cases in which the search for the 'most plausible solution' instead of the exact solution could be very useful (e.g. for the diagnosis of a crack pattern). The 'most plausible solution' is the path to which, among different equilibrated load paths, is associated the lowest value of the total strain energy. This
approach can be carried out by very simple mathematical methods and, in many cases, seems to be very useful because it is able to immediately catch the 'dominant path' (i.e. the one followed by the majority of the total load) in order to highlight, immediately and easily, the failure mechanism and the relevant crack pattern.

In the following, according to this simplified approach, the results of the energetic analysis of the paths drawn in figures 1b-f performed by Palmisano and Elia [5] are reported. For further details regarding the strain energy calculus (including the depth of struts and ties), see [5].

The masonry wall is considered in state 2 (i.e. after the soil settlement but before cracking). Strain energy has been calculated according to [16].

The following assumptions have been made:

- the masonry wall is geometrically symmetrical and symmetrically loaded;
- masonry is treated as a homogeneous material;
- the masonry wall is loaded by a uniform gravitational volume load.

The following parameters have been considered for the masonry wall:

- $H$ is the total height of the wall;
- $B$ is the length of the wall;
- $S$ is the thickness (constant) of the wall;
- $\alpha$ is the length of the soil settlement;
- $\rho = \alpha/H$ is the length of the soil settlement normalised for the total height of the wall;
- $\gamma$ is the unit weight of the wall (i.e. the only load applied at the wall);
- $\omega = E_c/E_s$ is the ratio of the compression Young's Modulus of the wall to the tension one.
- $D_{TOT}$ is the total strain energy of the single model.

To compare the results, Palmisano and Elia [5] define a 'reference strain energy' $D_{REF}$ that is the strain energy invested by the total load of half wall to reach the foundation soil by a vertical direct path in compression. Hence, in the case under study the reference strain energy is

$$ D_{REF} = \left( SB \gamma^2 H^3 / (8E_s) \right) \quad (1) $$

In figure 2 the ratio $D_{TOT}/D_{REF}$, in the case of lateral settlement, has been plotted for $\omega$ equal to 1. To plot these diagrams, the following assumptions have been made:

- $H = 6$ m;
- $B = 18$ m;
- for $LP(1)$, $LP(2)$ and $LP(4)$ the axis of the top chord is $H/10$ distant from the top edge of the panel;
- for $LP(2)$, $LP(3)$ and $LP(4)$ the axis of the bottom chord is $H/10$ distant from the bottom edge of the panel;
- the width of the longitudinal chords has been assumed as the maximum value consistent with their positions without causing superimposition of the chords.

The assumed value for $H$ and $B$ are typical for ordinary masonry buildings in Italy. Moreover, having assumed the half-length of the wall longer than its height allows to better evaluate the influence of the settlement length on the load path layout.

The normalised ratio $D_{TOT}/D_{REF}$ quantifies the increase of strain energy in the panel due to settlement and gives the opportunity to immediately catch which is the 'most plausible path' (i.e. the one with the minimum value of the total strain energy).

It is worth noting that in all the cases showed in figure 2, $LP(5)$ is the 'most plausible solution'. This is a direct consequence of the above-mentioned consideration about the saving in the strain energy of this load path due to the elimination of the thrust path in the middle of the panel.

The proposed approach is not aimed to quantify the ultimate capacity of masonry walls when subjected to landslide movements but it is aimed to show the effectiveness of the Load Path Method for the prediction of structural behaviour. In this scenario, simplified assumptions (e.g. calculus of strain energy in the elastic conditions) seem to be extremely effective.
3. Optimization of the results by using the BESO method

In this paragraph, the results obtained by the LPM are optimized by using an evolutionary optimization procedure.

Shape optimization is a method that enables designers to find a suitable structural layout for the required performances. The ‘Evolutionary Structural Optimization’ (ESO,) method was first proposed by Xie and Steven [18] in the early 1990s and it has been used to solve a variety of size and shape optimization problems. The basic concept of such a method is that by slowly removing inefficient materials, the structure evolves towards an optimum.

According to the ESO method, the stress level in any part of a structure can be determined by conducting a finite element analysis. A reliable indicator of the inefficient use of material is the low values of stress (or strain) in some parts of the structure. Ideally the stress in every part of the structure should be close to the same safe level. This concept leads to a rejection criterion based on the local stress level, where the low-stressed material is assumed to be under-utilized and it is therefore removed subsequently. The removal of material can be conveniently undertaken by deleting elements from the finite element model.

The stress level of each element is determined by comparing the Von Mises stress of the element $\sigma_{VM,e}$ with the maximum Von Mises stress of the whole structure $\sigma_{VM,max}$. After each finite element analysis, elements which satisfy the following condition are deleted from the model:

$$\frac{\sigma_{VM,e}}{\sigma_{VM,max}} \leq RR_i$$  \hspace{1cm} (2)

where $RR_i$ is the current rejection ratio (RR) at step $i$.

Such a cycle of finite element analysis and element removal is repeated using the same value of $RR_i$ until a steady state is reached, which means that there are no more elements being deleted using the current rejection ratio. At this stage an evolutionary rate, $ER$, is added to the rejection ratio, i.e.

$$RR_{i+1} = RR_i + ER$$  \hspace{1cm} (3)

With the increased rejection ratio, the iteration takes place again until a new steady state is reached.

The evolutionary process continues until a desired pre-fixed optimum is obtained.

The validity of the ESO method depends, to a large extent, on the assumptions that the structural modification (evolution) at each step is small and the mesh for the finite element analysis is dense. If too much material is removed in one step, the ESO method is unable to restore the elements which might have been prematurely deleted at earlier iterations. To make the ESO method more robust, a Bi-directional ESO method (BESO) was proposed by Yang et al. [7]. It allows for efficient materials to be added to the structure at the same time as the inefficient ones are being removed. Since its creation, BESO method has undergone many improvements. For the details concerning the BESO algorithm used in the analyses presented in this article see Huang and Xie [19].
To assist the selection of optimal shapes for the minimum-weight design of continuum structures with stiffness constraints, the performance of the resulting shape at each iteration can be evaluated by a Performance Index $PI$ defined as:

$$ PI = \frac{(C_0W_0)}{(C_iW_i)} \quad (4) $$

where $W_0$ is the actual weight of the initial domain, $C_0$ is the strain energy of the initial design under the applied loads, while $W_i$ and $C_i$ are the same quantities of the current design at the $i$-th iteration. It follows that to the optimal configuration will correspond the highest $PI$.

Equation (4) shows that the performance index is a dimensionless number; it is composed of the strain energy and the weight of a structure in an optimization process. This performance index is called the energy-based performance index.

By systematically eliminating elements with the lowest strain energy density from a continuum structure, the performance of the structure can gradually be improved. The larger value of the performance index means the higher performance of a structural shape.

Hence this performance-based optimality criterion is based on finding the value that maximise the performance index. This performance-based optimality criterion means that the optimal shape of a continuum structure under applied loads is achieved when the product of its associated strain energy and material consumption reaches a minimum. The optimal structure obtained represents an efficient load carrying mechanism within the design domain. The performance index can be employed to monitor the optimization process so that the optimum can be identified from the performance index history.

The above-mentioned performance-based optimality criterion is consistent with the simplified energetic criterion mentioned by Schlaich et al. [2] and, hence, with the load path method.

In the following, the application of the BESO method to the cases shown in paragraph 2 is presented. As previously said the aim is to use the BESO method to optimize the results obtained by using the Load Path Method.

The wall has the same dimensions of that described in paragraph 2. The thickness of the wall is 0.30 m.

The numerical analyses have been performed using the Finite Element code ABAQUS 6.7-EF1 [20]. The domain has been subdivided into a regular mesh (0.1 m x 0.1 m) using the linear quadrilateral (type CPS4) finite element. The compression Young's modulus of the wall ($E_c$) and the Poisson's ratio have been assumed equal to 4500 MPa and 0.25 respectively.

The assumed values of $\gamma$ and $E_c$ are consistent with Table C8A.2.1 of [21] for brick walls whereas the value of the Poisson's ratio is consistent with [22].

The applied load is only the unit weight of the wall $\gamma = 12$ kN/m$^3$.

The main aim of the strut-and-tie approach and, hence, of the BESO method is to transform a continuum body into a discrete one. This means that distributed loads should be transformed into discrete loads (applied in the nodes of the model). In general, it is not possible to define a priori an equivalent number of discrete loads. In this scenario, in the case under study, preliminary sensitivity analyses have been performed to define the minimum number of equivalent discrete loads that allow to immediately catch the structural behaviour and to compare it with the results of the LPM approach. This is why, only regarding the applied load, the wall has been divided into ten vertical strips. The uniform applied load has been transformed in ten point loads applied in the centroids of the vertical strips.

The bottom part of the wall, in the zone not subjected to settlement, is restrained by elastic vertical springs to simulate a Winkler soil. The stiffness of the springs is equal to 10 kN/m to have a constant soil pressure distribution (i.e. consistent with the assumptions of paragraph 2). In order not to have tension in the vertical springs, these have been distributed only in the reacting central part of the soil according to models in figures 1b-f.

The central node of the bottom of the wall is horizontally fixed. It has been checked that there are no analyses in which this node is removed.
The BESO3D software adopted for the analyses is developed and provided by the 'Centre for Innovative Structures and Materials (CISM)', RMIT University, Australia.

The BESO parameters are $ER = 0.5\%$, $AR_{\max} = 1\%$, $r_{\min} = 0.3$ m (three times the size of one element) and $\tau = 0.1\%$. For the significance of $AR_{\max}$, $r_{\min}$ and $\tau$ see [19]. Analyses for $\rho = 0.3$, $\rho = 0.6$ and $\rho = 0.9$ have been performed. Figure 3 shows the optimal shape.

![Figure 3](image)

**Figure 3.** Settlement that involves the lateral part of a masonry wall. BESO analysis. Optimal shape ($\omega = 1$) for $\rho = 0.3$ (a), $\rho = 0.6$ (b), $\rho = 0.9$ (c)

In the case study, having assumed the half-length of the wall longer than its height allows to evaluate if, varying the settlement length, all loads follow the same path shape or if the shape depends on the distance of the load from the area not subjected to the settlement.

In all cases under study (Fig. 3), BESO results show that loads located either above the settlement area or close to that area follow a path similar to $LP(5)$ in figure 1f.

A difference can be noted for the other loads. In fact, for $\rho$ equal to 0.3 or 0.6 (Figs. 3a-b) the other loads follow a direct compression path generating an additional compression longitudinal chord in the middle of the wall (i.e. $LP(3)$ of Fig. 1d). According to the LPM, this is a direct consequence of the circumstance that, for $\rho$ equal to 0.3 or 0.6, these loads, undergoing a slight deviation, generate thrusts very low in value. It follows that the strain energy of the middle longitudinal chord should be very low too. This is why, in this scenario, to save strain energy, the travelling loads prefer to follow the shortest path (i.e. the direct compression one).

On the other side, for $\rho = 0.9$ (Fig. 3c), loads which are not close to the area involved by the settlement, undergo not negligible deviations and hence follow a path similar to $LP(5)$ of figure 1f to save strain energy (i.e. that associated to the middle longitudinal chord).

From the comparison between these results and those presented in paragraph 3, it can be noted that, as suggested by Mezzina et al. [3]), the BESO approach is very useful to optimize the results obtained by using Load Path Method.

### 4. Conclusions

Following Roca et al. [4], who sustain simple methods based on fundamental principles (e.g. limit theorems of plasticity) as still crucial to catch on the primary aspects of the structural response, Palmisano and Elia [5] have shown demonstrate the effectiveness of the Load Path Method in the interpretation of the behaviour of masonry buildings subjected to foundation settlements due to landslide.

The LPM is very useful for finding the 'most plausible solution' instead of the exact solution. This approach can be carried out by very simple mathematical methods and, in many cases, seems to be very useful because it is able to immediately catch the 'dominant path' (i.e. the one followed by the majority of the total load) in order to highlight immediately and easily, the failure mechanism and the relevant crack pattern.
In this scenario, this article has shown that the BESO method is very useful to optimize the strut-and-tie models obtained by using the LPM in masonry buildings subjected to landslide-induced settlements.

Further theoretical work is needed to quantify the ultimate capacity of masonry walls in the above-mentioned conditions. Nonlinear and anisotropic behaviour should be implemented in the method and comparison of the results with those of laboratory tests is needed.

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