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A first approach to the load path method on masonry structure behaviour

G. De Tommasi[1], P. Monaco[2] & C. Vitone[2]
[1] *Department of Architecture and Town Planning, Bari Polytechnic, Italy.*
[2] *Department of Civil and Environmental Engineering, Bari Polytechnic, Italy.*

Abstract

Since ancient times, architects have made use of models to create ideas and to have a concrete object to work with. Only after Galilei did this custom enter into the heritage of Science and then models become also instruments to simulate and to analyse the structural behaviour. Drawing inspiration from the truss model that dates back itself to the birth of r.c. at the end of the nineteenth century (Hennebique, Ritter and Morsch), the *Strut and Tie Model* (*STM*) was recently proposed by the Stuttgart School in a wide application to r.c. structures. In the meantime interest grew in methods to generate the *STM*, as *LPM* (*Load Path Method*: Schlaich, 1996). The systematic and organic use of *LPM* (A.Vitone, Palmisano et al., 2002) is especially useful to give frames the physical significance of load paths, offering the possibility of immediately evaluating the link between form and statics (Heyman [6]), geometrical dimension and intensity of strain and of controlling the output of numerical automated analysis with finite elements (*FEM*). These models bring back structural analysis to the study of compression and tension flows and seem to be particularly suitable to masonry structures that, because of their constructive and geometrical characteristics, avoid the simplifying hypothesis at the origin of the *Technical Theory of Beams*. This study tries to propose itself as a preliminary contribution to *LPM* application to masonry structures. In geometrical contours and in some physical aspects it is possible to recognise the trace of loads flowing: from interrupted and deserted paths to different explorations of alternative routes in a dynamic study of static equilibrium moments in which the history and then the life of structure identify themselves.

1 Load Path Method: the origins

Strut and Tie Method (STM) has been conceived as a simple representation of the involved static behaviour of a r.c. element subjected to shear and bending. It was introduced by W. Ritter (1899) who proposed a simple truss model in order to study r.c. cracked beams on the basis of an idea of François Hennebique and then developed by W. Ritter himself and by E. Morsch who looked for a first organic application for the design of r.c. beams. In the twentieth century several studies (Rausch,1929; Chambaud, 1957; Kupfer, 1964; Nielsen, 1967; Nielsen & Baestrup, 1975) have been done about STM and the results became the basis of some prescriptions in Danish Code DS411 and in Model Code 1990 (CEB-FIP [2–4]). When plasticity theory has been applied to concrete, the Zurich School (Marti, Muller) has proposed a generalisation of some concepts taken from the analogy with truss by introducing discontinuous compression fields (struts) in equilibrium with ties. Later, F. Leonhardt of the Stuttgart School has made a wide application of the model to r.c. structures design. The accuracy of the results mainly depends on the way the model fits the actual structural configuration. However it is necessary a special care to design the model geometry. Having to draw inspiration from even brief expectation of structural behaviour, this care gives back to human sensibility the task of restoring harmony between technical contents and formal choices, since the first time of the design (Croci [5]). In this scene, the searching of instruments that reproduce less empirically the choice of model design, such as Load Path Method (LPM) becomes necessary. The Load Path Method has been officially mentioned for the first time by Jorg Schlaich and Kurt Schafer [3] during a Workshop in Taiwan (1996). Its application to masonry structures seems to be particularly suitable because of their constructive and geometrical characteristics (Giuffrè [7]).

2 Load Path Method: basic principles

The classical Bernoulli model is successfully applied to "*B*" regions (*B*eam, *B*ending, *B*ernoulli) of a r.c. structural element . Anyway, this approach has to be left for "*D*" regions (*D*iscontinuity, *D*isturbance, *D*etail) in which there are local geometrical and static singularities. The interest for a unique model (STM) capable to analyse both regions grows only during the last century, since it has been understood the great influence that the correct design of the "*D*" regions has in the behaviour of the whole structure. Today STM is officially mentioned by international codes, such as Eurocode 2 [1], and its application to r.c. structures is wide. Masonry structures, because of their constructive and geometrical characteristics, avoid the simplifying hypothesis at the origin of the Technical Theory of Beams and the research of a truss model that gives a solution equilibrated and congruent at the same time, could be difficult. This becomes a huge problem especially when the technician can not make preliminary evaluations of the behaviour of a complex structure, subjected to multiple load

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and constraint conditions, only using his intuition and his experience (Elia [8]). In this scenery the Load Path Method becomes particularly effective in the phase of choice of the model that best fits masonry structure.

The most suitable orthonormal Cartesian system of architectural forces to physical environment in which they flow, is that is capable to bring back them only to vertical loads and horizontal thrusts. According to this, structure can be read as the trace of loads path. The form of the structure is the result of their mutual integration and mainly of the influence of profiles traced by thrusts path, forced to deviate their natural horizontal flows to the soil, in order to go in search of equilibrium. Forces represent loads that, in the way from their application points (S) to the restraints (E), in every deviation node have to apply thrusts (H) to the rest of the structure and to receive deviation forces equal and opposite to thrusts in order to respect equilibrium (fig.1).

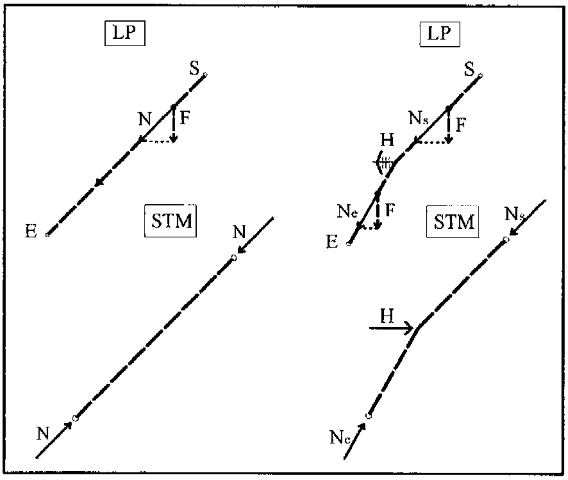

Figure 1

The design of this load flowing through the structure can be approximated by polygonal lines in which there are thrusts in every deviation node. The degree of approximation depends on necessities of analysis. Structure will be crossed by compression fluxes (dashed lines), when loads travel in the same direction of their path, and by tension fluxes (continuous lines) along which loads go in the opposite direction respect to their path. According to classical theory, the basic principles that lead Load Path Method are the respect of equilibrium and congruence. Thrusts in deviation nodes are necessary in order to respect equilibrium and every path is possible if it is equilibrated.

Between infinite paths in equilibrium, loads have to choose the one in which their vectors invest the minimum quantity of strain energy, that is the only one

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equilibrated and congruent. At this purpose loads get energy from their own potential energy that decreases. Along a generic path (polygonal in this model), the calculus of the invested strain energy (D) is simplified in the summation of the terms relative to every side of the traverse:

$$D=(1/2)\Sigma\, N_i*l_i*\varepsilon_i$$

"$_i$" is the generic side of the load path; N_i is the intensity of the *vector* that *brings* load on that side of the load path; l_i is the length of the generic side and ε_i is the relative strain that is medium constant on l_i. In the following part of this paper a review of applications of the method to masonry structures is presented; the aim is to try to recognise inside the structure the less dissipating paths and, among them, the one in tension that will become fundamental for both interpreting a possible existent pattern of cracks and for making a prevision about the one that occurs after the formation of the first cracks. LPM brings back the analysis of cracks patterns to the search of compression paths along which loads flow and against which cracks appear interrupting paths in tension (see figures 5-6-11-13). According to this method the cracks width represents an indirect measure of strain energy employed by loads forced to leave interrupted paths in the search of new ones.

3 LPM: from the constructive detail to the structural organism behaviour

3.1 Mortar joint crossing

A model for the case of friction which occurs between two surfaces in contact belonging to two different bodies can be showed using Load Path Method. The basis assumption is that load path can go through the boundary only by paths perpendicular to boundary sides. Therefore load can cross slantwise a joint (i.e. horizontal) only if the surfaces in contact offer tilted sides (with respect to horizontal plane) to load. In the model, tilted sides are the graphical representation of roughness (fig. 3). The local microscopic analysis using the Load Path Method with the application of conditions of equilibrium and congruence (minimum thrusts path) gives clear perception of the influence of the many factors on which depends the model of the case of friction.

Starting by the sketch of horizontal load path (H) it is possible to trace consequent thrusts paths (V). In this case, load H directed along the path inclined of the angle θ (fig. 2), is forced to deviate and to take the path ABCD (fig. 3), in order to cross the joint and take again its inclined path. In deviation nodes vertical thrusts V occur. By this model it is possible to gather clearly the following topics. The perfect bonding between mortar and masonry block assures continuity in the load path. The mortar tension strength is necessary to make the load H getting the closest asperity along the joint in order to cross it, even if moving back. The vertical thrust V is necessary to guarantee local equilibrium, otherwise compromised by the inevitable translation of the path of H.

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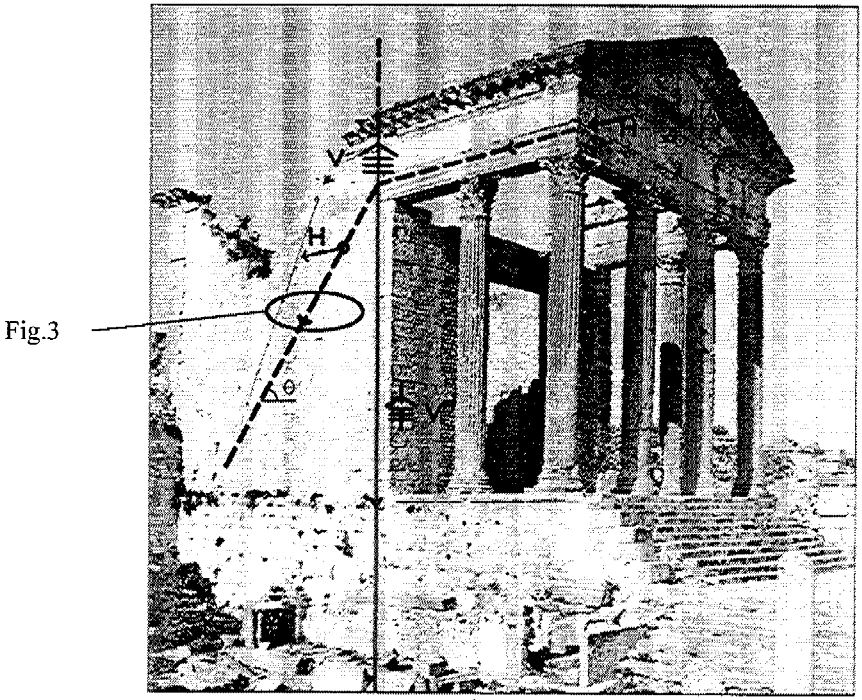

Figure 2

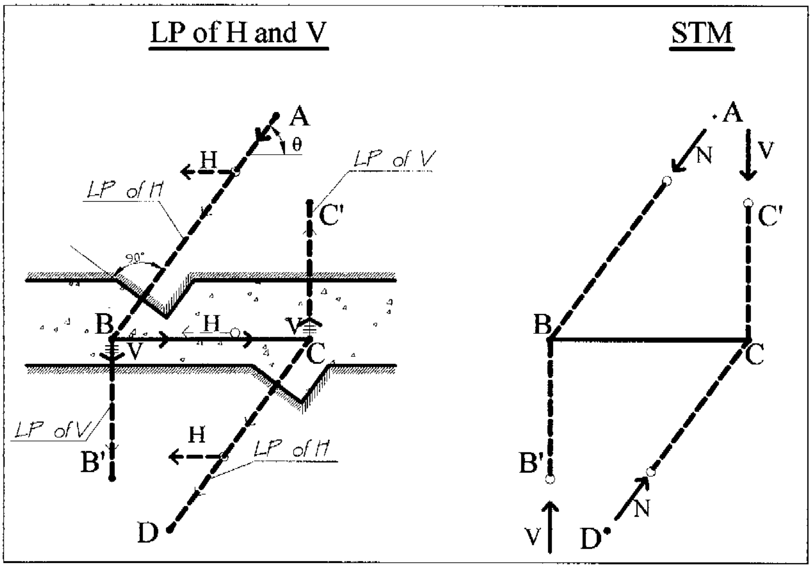

Figure 3

3.2 First crack formation and phenomenon progression

In this part of the paper a not homogeneous body with uniform imperfections is analysed (fig. 4).

On path in tension the intensity of vector is constant following the definition of load path itself and the specific condition of path in a rectilinear direction. At the same time, according to the assumption of uniform material, the strength of each section crossed by tension flux is constant. The assumptions of constant stress in the section should make indeterminate the section in which the first crack should grow (fig. 5). However, this condition is disturbed by orthogonal compression fluxes. In the section in which the impact between the two fluxes occurs, even if the hypothesis of uniform strength characteristics is still valid, the assumption of constancy of the tension vector becomes no more valid (fig. 6).

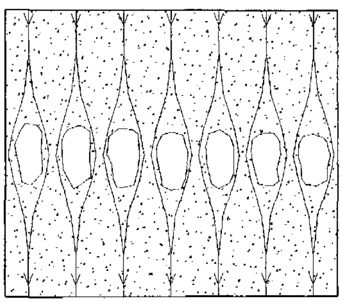

Figure 4

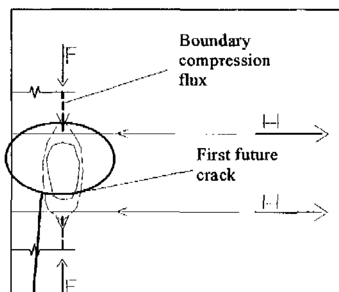

Figure 5

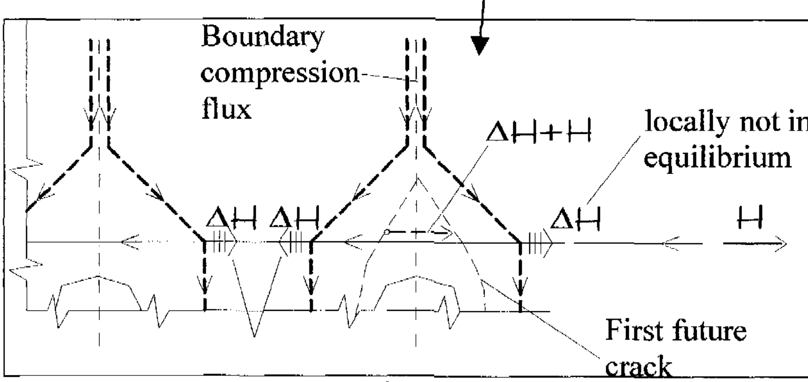

Figure 6

The vector ΔH, that *brings* thrusts occurred in the deviation nodes of the orthogonal compression flux, is added to vector H. Thrusts ΔH exist as a consequence of the initial assumption of not homogeneous body. The first crack

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appears in the section where the impact between the two fluxes occurs (fig. 6). A confirmation to this fact is given by energetic considerations. According to previous assumptions, the solution that implies the minimum strain energy is that with shortest thrusts path l_i, at a parity of ε_i and N_i.

3.3 Failure in a compression test

Failure under compression can be seen as a failure that occurs perpendicularly (see paragraph 3.2) to path in tension (orthogonal to those in compression).

If a body with the same characteristics described in the previous paragraph is subjected to a uniformly distributed vertical load (i.e. by a platen), tension horizontal fluxes will occur because the platen is a restraint for the free side-expansion of the body and above all to the fibres that are nearest to the platen itself. In this case the model, in which the fact that it is not homogeneous is represented by a uniform distribution of imperfections, is particularly effective because it simulates the horizontal strain by the extension of horizontal fibres caused by horizontal thrusts occurred in the deviation nodes of the vertical load path. The vertical load path deviates in order to avoid imperfections (fig. 7).

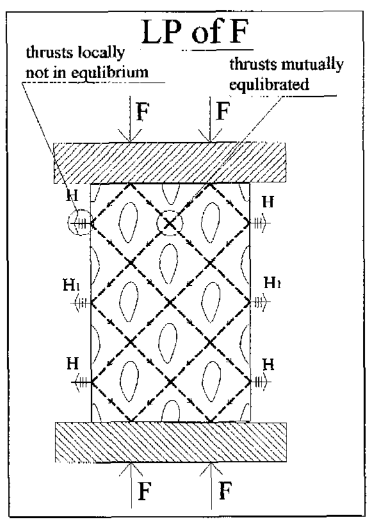

Figure 7

According to this model the outermost thrusts are the only not in mutual local equilibrium and in order to get it those on a side will try to equilibrate thrusts on the opposite side. In the case in which the stiffness of platen is bigger than that of the body (E_{platen}>>E_{body}), thrusts H near to platen in order to equilibrate themselves enter into the platen because this is the less dissipating path; they can go into the platen because of friction between platen and body (fig. 8). Thrusts

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H_l could get equilibrium inside the body, since they are too far from the platen.

In the opposite case in which E_{platen}<<E_{body}, only thrusts path inside the body occurs (fig. 9).

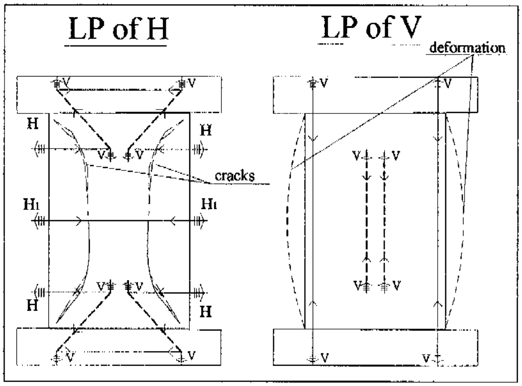

Figure 8: E_{platen}>>E_{body}

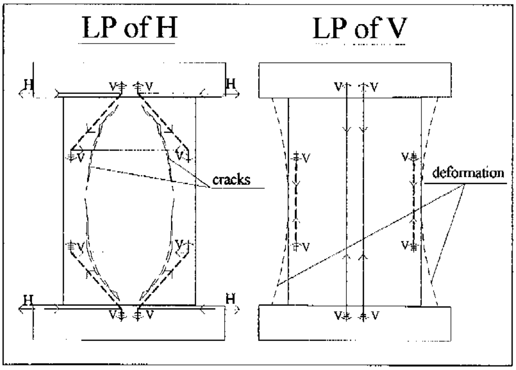

Figure 9: E_{platen}<<E_{body}

3.4 Towards the macroscopic analysis: cracks draw load path

By microscopic analysis at previous paragraph it is possible to get inspiration for the comprehension of crack patterns occurred in the same assumptions. In a masonry nucleus between two openings (fig. 10), a crack pattern perfectly in accordance with previous microscopic treatment appears at the cross impact section between horizontal in tension and vertical in compression fluxes. Crack pattern draws the boundary of loads path, deviated to spread in order to spare strain energy. Loads coming from above that have to avoid the upper opening, will concentrate at its embrasures. Between the two openings loads will spread in

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order to spare strain energy before deviating and concentrating again at the embrasures of the lower opening (fig. 11).

Figure 10: cracks coloured in white.

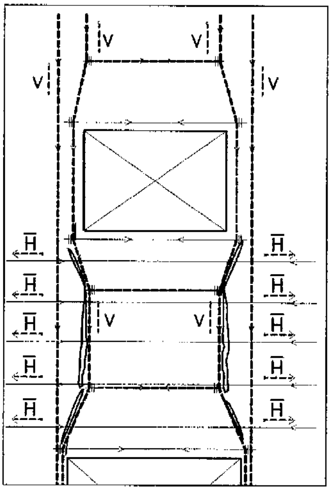

Figure 11: LP of fig. 10.

3.5 Foundation settlement

In a zone interested by a foundation settlement (fig. 12) soil can't equilibrate loads coming from the top.

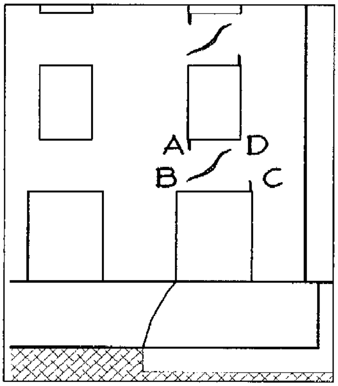

Figure 12

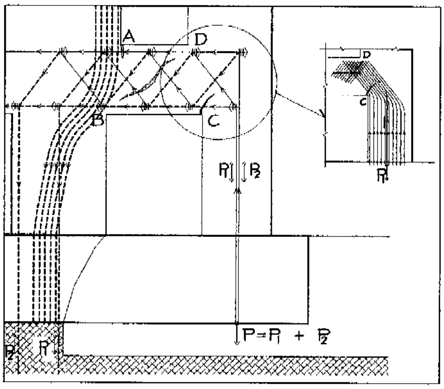

Figure 13

Hence loads will change their original path in search of a new equilibrated

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configuration (fig. 13). According to the path in fig. 13, cracks occur orthogonal to the path in tension where the transversal section is the smallest one, and at the cross section impact between path in tension and the compression flux coming from the top of the building.

4 Conclusions

A first proposal of the use of LPM basic principles to masonry structures has been presented in this paper. This first approach has been made in order to show LPM versatility and STM effectiveness. The model is capable to simulate structural behaviour simply by the perception of adhesion of its geometrical profiles to the *form*. Passing through analysis up to STM optimisation, from constructive detail up to a global approach to a structural organism, LPM seems to successfully conciliate the necessity of getting also a numerical solution and that of never losing touch with the perception of the synthesis of physical structure's behaviour.

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