Load Path Method (LPM) in Detailing Design

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INTRODUCTION

The latest technical standards tend to identify design objectives in a framework much more complex than the one of the past codes. This tendency arises from the necessity to satisfy in a proper way the owner structural reliability demand. In fact, the owner is getting more and more exacting because of the increase of the ratio of the total value of the works to the structural construction cost on which mainly the preservation of that value depends. For r.c. structures, the request to adequate performance objectives is particularly urgent. The ratio of the hazards which structures can be subjected (not only accidental actions) to the r.c. structures reliability, estimated also on the basis of their behaviour in the last century, is increasing. There have been many flops: damages, often of unexpected seriousness, caused by earthquakes; tragic collapses, happened with disastrous mechanism disproportionate to the original cause; premature, if compared to expectations, deterioration.

Fig. 1. Design objectives, from detailing to structural body general conception in an organic framework of performance objectives. Basic requirements: instruments to reach performance objectives.

In Fig. 1 an organic framework of performance objectives and basic requirements, starting from EN 1990 [1], is proposed. It is immediately noticeable that safety has a central role, that durability is extended to the requirements of the higher objectives and that there is the necessity to modulate rules, methods and requirements depending on reliability. This is a proper guideline from structural global conception to detailing. Some ‘steps’ to follow in order to pursue the performance objectives above mentioned, are listed:
(1) Choice of the model.
(2) Evolution reconstruction of the structural body configuration (first line in Fig. 4).
(3) Physical transformations definition (fourth line in Fig. 4).
(4) Energetic interpretation.
(5) Structural behaviour analysis in each transformation.
(6) ULS structural behaviour analysis (fifth line in Fig. 4).
(7) Creation of models that can simulate ‘States’ (mod. S, third line in Fig. 4) and ‘State Transformations’ (mod. T, fifth line in Fig. 4).
(8) Comparison between the model and the cracks pattern morphology.

Keywords: strut-and-tie model, Load Path Method, strain energy

PROCEDURE

As above mentioned, the procedure suggested both for detailing and for the whole structure behaviour investigation, should be conceptually the same. In the next paragraphs, the eight ‘steps’ previously listed, in which the procedure can be subdivided are explained, followed by an application of the procedure on a frame corner.

First step: choice of the model

With regard to the first step listed before, nowadays it is recognised [2] that strut-and-tie model (STM), thanks also to its versatility, has the capacity to simulate the most various behaviours, not only the local ones. A proof of its versatility is in the fact that the model can represent both different ‘States’ and ‘Transformations’ that allow the structure to pass from a state to another (Fig. 4). Therefore it seems particularly useful the use of a method, like the Load Path Method (LPM) [3-10], that, giving each member of the STM a specific physical meaning, can evaluate the model reliability since its conception. Even if particularly useful in the analysis of discontinuity regions, it has to be recognised that LPM can simulate the typical behaviours of beam regions, with a level of precision depending only on the designer’s will [7].

STM fundamental characteristics

Adopting STM, as proposed at step (1), it is possible to find three ‘characteristics’ of the model, essential to define its behaviour:

(a) the organisation of its constitutive elements (both the overall ‘form’ and the ‘form’ in the details: topology, inclination, number of the members converging in a node);
(b) the requirements of every member (stiffness, strength, ductility, redundancy) both in absolute and in relation to the other members of the model (robustness, capacity design);
(c) nodes characteristics.

Load, Thrust and Vector Path (LP, TP, VP)

To design a STM it would be better to evaluate step by step the type of action for which the path into the structure has to be reconstructed: the load path (LP), the thrust path (TP), the vector path (VP) or their combination (Fig. 20). Looking at the examples in Figs. 3A and 3B, taking into account the symbols reported in Fig. 2, the VP well fits the case of longitudinal continuous bars: the transversal bars have to be added separately. The convenience of the VP use in reinforcement design, when bars are continuous, between two sections (S and E), is particularly evident when in these ‘stations’ the directions but not the intensities of the vector are different (Fig. 22, VP of Nt). Fig. 3B shows for the same case that the LP is more suitable to simulate the cases of beam longitudinal bar diagonally bent, and of column longitudinal bar separated from the one of the beam. The VP is useful to represent the path in tension on bars that keep the same cross section along the entire path, also not rectilinear. Otherwise along the LP, the intensity of the load bearing vector is changing according to the inclination of each part of the path. If redundant cross sections are available, this circumstance is not a problem for compression paths in concrete. On the contrary, for tensile paths, it involves a change of the strictly necessary reinforcement cross section. This is the case of the part 2-3 represented in Fig. 3B, in which another bar has to be added to the bar coming from the beam. In the
following, a distinction between loads paths (LP) and thrusts paths (TP) in deviation nodes has been made, as shown in Figs. 18 (VP, LP) and 19, 20 (TP).

<table>
<thead>
<tr>
<th>Compression Path (LP)</th>
<th>Tensile Path (LP)</th>
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<tr>
<td>Load goes down</td>
<td>Load goes up</td>
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<tr>
<td><em>S</em></td>
<td><em>E</em></td>
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<tr>
<td><em>N</em></td>
<td><em>N</em></td>
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<td><em>F</em></td>
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**Fig. 2.** Symbols.

**Fig. 3A.** VP of N and V.

**Fig. 3B.** LP of N (U-TURN) in the beam and TP in the column.

**Second step: evolution reconstruction of the structural body configuration**

During its design working life (see first line in Fig. 4), the structural body configuration undergoes several ‘evolutions’ (see next step). The whole process can be brought back to the sequence of a limited number of instantaneous ‘configurations’ (‘States’), each one caused by a specific ‘State Transformation’. The structural
behaviour analysis can be reduced to the verification of those configurations and of the corresponding transformations.

Fig. 4. Structural body evolution to ULS. ‘States’, ‘State Transformations’ and the relative models.

**Third step: physical transformations definition**

This paragraph concerns structural body physical transformations and the subsequent ones to which loads paths are obliged (see the fourth line in Fig. 4).

*Physical* transformations

Physical transformations consist of changes in the structural body physical characteristics. Deformations from a configuration to another can occur as a consequence of actions (loads) coming from outside the structure and according to a fixed behavioural law that is characteristic of the state in which the structural body is (the first item in the fourth line in Fig. 4). Physical transformations can occur also because of phenomena that modify structure behavioural laws, without introducing new actions. First crack formation, cracks patterns evolution, bond loss of the bars caused by their sliding (2nd, 3rd and 4th ones in Fig. 4), stiffness changes (of the cross section, of the structural element, of the whole structure) because of damaging or chemical transformation of structural materials, etc., belong to the latter case.

*Loads paths transformations*

Loads paths transformations consist of loads and vectors paths changes. In fact, loads and vectors leave paths (or parts of them) that have become less stiff or completely compromised because of physical transformations, to go in search of paths on which they dissipate less strain energy.

**Fourth step: energetic interpretation**

A transformation can be interpreted as a change in the nature of energetic resources of the complex system to which the structural body belongs. The potential energy and/or the kinetic energy of masses become strain energy stored in the structure, and/or partially ‘dissipate’ or transform themselves in other forms of energy not reversible in mechanical energy. The cracks formation modifies the mechanical characteristics of loads paths that become not representative any more of paths to which the minimum strain energy...
investment corresponds. To go in search of the new ‘optimum’ configuration, loads are forced to change their path and to do further work, investing the complex system resources in order to have at their disposal the strain energy necessary to ‘open’ less dissipative paths. The cracks ‘bypass’ (Figs. 12 and 13), and the activation of the reinforcement along tensile paths belong to this scenario. After cracks formation, in fact, less dissipative tensile paths along bars are preferred to tensile paths in concrete, stopped by the discontinuity.

Fifth step: structural behaviour analysis in each transformation

In general, an opinion on structural behaviour has to be expressed in relation to the performance objective that has to be verified. The verification of strength capacity (objective a’’ in Fig. 1), for example, is usually measured evaluating the probability to reach the ULS and comparing this probability with the corresponding design value, that is the maximum between the value given by standards and the one requested by the owner. As above mentioned, several ‘basic requirements’ contribute to reach the ULS performance objective: ductility, over-determination, redundancy, capacity design, robustness (Fig. 1). The reliability evaluation that has to be carried out at the transformation from State I to State II (first crack) is another significant example. This evaluation consists of the verification of the structure capacity (or of the detail capacity: see Figs. 12 and 13) to give loads, generated by cracking, self-equilibrating alternative paths (Fig. 4: mod. C.T.), limiting the local damage. More in general, evaluations on the limitation of damages caused by transformations from a State to another have to be done with regard to the performance objectives: functionality, aesthetics, economy, durability (Fig. 1). Of course, evaluations have to be done with regard to the safety structural objective (a) and to the effects that a damage consequent to a transformation state has on the structural behaviour in the other States, and in the ULS in particular. In other words, the evaluation of the structure capacity to transform itself is needed. A criterion to evaluate this capacity can be the measure of the further energy that has to be transformed for this purpose. It is also important to verify that compression paths in concrete do not undergo premature damages. These paths, in fact, are essential with regard to the STM, working at ULS, to give the structure, in extreme conditions, the possibility to use all its strength resources.

Sixth step: ULS structural behaviour analysis

The analysis of the structural behaviour at ULS, see fifth line in Fig. 4, has to be carried out on a model capable of simulating this particular state, conventionally corresponding to the end of the structure life. Of course, the model has to reproduce only the possible loads paths, that is to say the ones in compression in concrete and the ones both in compression and in tension in the bars. The concept of ‘possibility’ at ULS resides in the simultaneous satisfaction of conditions of both equilibrium and compatibility with the fixed conventional ‘design’ values of the strains in the resistant materials, concrete and reinforcement steel. Then, it has to be assumed the reinforcement layout independently of the fact that it can be more or less ‘consistent’ with tensile fluxes before cracking (compare Figs. 8 and 7). In Fig. 4 it has been assumed as extreme configuration the one that involves the bars sliding. In the case shown in the following, Figs. 16 and 22 represent respectively the State II (after cracking evolution but before bars sliding) and the ULS (after bars sliding) reported in Fig. 4.

Seventh step: creation of models that can simulate ‘States’ and ‘State Transformations’

The creation of strut-and-tie models (using LPM) representative of ‘States’ and of ‘State Transformations’ (see Fig. 4: mod. S., third line and mod. T., fifth line) is necessary to verify the structure behaviour for all its working life. As mentioned at step (6), all these ‘phenomena’ can be brought back to transformations of the complex system energy (masses + structure). When the transformation concerns the energy transferred to the structure from masses (that loose the same quantity of kinetic and/or potential energy), the model is made up of loads that, starting from masses, go through the structure up to external restraints. The ‘actions’ (loads in the LPM) represent the instrument to make these transformations happen. In Fig. 4 models that simulate this particular phenomenon are the S.T. models. This phenomenon occurs when a mass, subjected to seismic or gravitational acceleration, makes the structure become deformed in order to remain constrained to the structure. This particular type of transformations can obviously concern the structure in all its States, briefly reported in Fig. 4. However, when the transformation concerns only the structure energy without the energy transfer between masses and structure, the model representative of the phenomenon (mod. C.T.,
Eighth step: comparison between the model and the cracks pattern morphology

The comparison between the model and the cracks pattern morphology (Figs. 22 and 23), in the phase in which these phenomena have occurred, can be extremely useful. The comparison, in fact, allows to increase the 'preliminary' diagnostics capabilities, based on empirical observations but justified by their verification based on simple models. Therefore it helps in supporting experience at the conclusion of the theoretical analysis. To this purpose also the use of LPM is particularly effective [9, 10].

REINFORCED CONCRETE FRAME CORNERS

In this paragraph the case of the frame corner with ‘opening moment’ and, in particular, the reinforcement layout type 4 in Fig. 7 is presented. This reinforcement layout is one of the seven different solutions examined in a well known experimental study [11] from which Figs. 5 and 6 have been taken. In Figs. 8, 9 and 10 models that simulate State I without cracks are shown: the complete STM, the longitudinal actions VP and the TP. These are ‘concentrated models’ that could be obviously improved simply separating actions into a higher number of equivalent elementary loads [5].

The first cracking phenomenon (mod. C.T. in Fig. 4) that leads structure to State II of first cracking (Fig. 11), according to step (7), can be represented using the ‘circuit’ of loads F (Fig. 13). In order to better point out its fundamental aspects, in Fig. 12 the model obtained concentrating loads and subsequently substituting the curvilinear path with the circumscribed polygonal one is shown. The loads F (that simulate cracking) are compression actions applied to the crack edges, equal in intensity but opposite in direction to the pre-existent tensile actions. ‘Generated’ by cracking phenomenon, loads F leave the ‘station’ S and reach equilibrium at ‘station’ E, ‘bypassing’ the crack.
It has to be pointed out that thrusts H have to be orthogonal to travelling load direction, because they are applied by LP vectors (Fig. 2). In Fig. 14 the thrusts path (TP) is represented separately in order to underline that also their paths, forced to avoid annular cracks, apply thrusts (T, in Fig. 14) in deviation nodes. Finally, the path of H is particularly weak since it is annular like the cracks. Using the model in Fig. 14, this ‘weakness’ is immediately noticeable. In fact, the direct path that would be followed by the two thrusts T to meet, would be a path in tension and orthogonal to the profile of the annular crack. Another cause of ‘weakness’, due to a similar reason, is the alternate path to which the thrust T is forced, from the edge of the annular crack to the internal corner. This path is actually close and parallel to the edges of the radial cracks.

In Fig. 15 a model of the transformation due to cracking corresponding to a reinforcement layout different from type 4 and similar to type 7 (Fig. 5), is shown. This model deals with a LP, from S to E, through the sequence of nodes 1-2-3-4-5. The circumstance that the diagonal axis is of symmetry makes action F split itself into two equal parts and assures the local equilibrium of the thrusts H in nodes 2 and 4. On the contrary, thrust H* finds its balancing one going back (Fig. 2) along the transversal reinforcement, between node 3 and its symmetrical one. In this case, anyway, thanks to the external part of the reinforcement layout, extended both into the beam and the column, compression paths, with a different inclination, can go through regions that are less damaged by annular and radial cracking. Besides, the reinforcement 3-6 ‘sews’ the radial crack, reducing its width, thanks to the less quantity of strain energy requested by the bypass of the loads generated by first cracking. They can in fact cross over the crack using the bars, following direct paths less dissipative than the ‘circuit’ ones shown in Figs. 12 and 13.

The model has pointed out two detail aspects: the necessity of a continuum reinforcement in node 2 (Fig. 15) to assure the equilibrium of the two thrusts H along a path that, even if localised, is in tension and the necessity to ‘cross’ the reinforcement in nodes 3 and 3’ to assure the local model, shown in the particular in Fig. 15. It has to be underlined that this model shows the possibility to realise a situation in which local equilibrium is reached thanks to three compressive paths.
According to the framework reported in Fig. 4, Fig. 16 shows the complete STM representing the State II, before ULS, in the condition of bars bond to concrete. In the same figure the VP of $N_t$ and the LP of $N_c$, mutually balanced, are presented. Fig. 17 shows the paths of the thrusts consequent to the LP of $N_c$ deviations. Nodes 5 and 4' (Fig. 16) tend to be in the internal part because of the bars bond that is hypothesised active in this phase.

Fig. 14. Mod. T.C.: concentrated TP.  
Fig. 15. Mod. T.C.: type 7 LP.  
Fig. 16. Mod. S.II: VP of $N_t$ and LP of $N_c$.  
Fig. 17. Mod. S.II: LP (U-TURN) of H.
Even if \( N_c \), deviating to go towards those nodes, can have at its disposal bigger concrete sections, the double deviation creates an additional couple of thrusts \( H \) that ‘counterbalances’ the reduction of the internal lever arm \( \Delta z \). In Fig. 17 the effects of this occurrence are shown: additional tensile paths that require further reinforcement localised in the frame corner. It can be useful to observe, comparing Figs. 16 and 13, that the diagonal compression path of \( N_t, 4'-5 \), follows itineraries whose weakness has been previously discussed using the first cracking model.

The transformation from the State II to the ULS reported in the framework in Fig. 4, is in this paper identified with the loss of bars bond along their annular part inside the frame corner. This circumstance is simply recognisable in the models by the orthogonal crash between compression (radial) paths and tensile (annular) ones (Figs. 18 and 22). Fig. 18 shows the extreme case to which the maximum reduction of the internal lever arm \( \Delta z \) corresponds. The real case is of course different and a likely model is reported in Fig. 22. Figs. 19 and 20 represent two different solutions for the additional force couples in the limit case of Fig. 18. In the first one the \( \Delta N \) tensile path is supposed equal to the \( N_t \) one (Fig. 18). In the second one, it is instead assumed a path corresponding to reinforcement layouts type 3 and 5 in Fig. 5. It has to be pointed out that diagonal bars in the latter case (TP 2-14,15 in Fig. 20) stop in node 14,15 only for consistency with the abstract limit model in Fig. 18. If otherwise the more realistic behaviour in Fig. 22 is considered, it can be recognised the necessity to extend that bars up to the external edge of the frame corner. This additional reinforcement is both necessary for the exposed reasons and useful to give loads fluxes, generated by annular cracking, paths through the crack more direct than the ‘circuits’ shown in Fig. 13.

The phenomenon of annular bars sliding in the frame corner causes damages in the surrounding concrete, clearly revealed by cracking patterns shown in Figs. 6 and 23. Then, the compression path of \( N_c \) has to deviate (nodes 12-13, Fig. 22) going towards the internal part of the frame corner to assure itself more intact resistant cross sections. Coming out from the critical region, using further deviations in nodes 16-17, the vector comes back towards the external part. In this way, the extension of the region in which there are the effects of the additional force couple, corresponding to the reduction of the internal lever arm, is reduced. The evaluation of \( \Delta z \) is also possible. In fact, \( \Delta z \) is the one necessary to give the design strain at ULS to the compressive available concrete section on the 14-15 path in Fig. 22 (that is to say, the one external to the region damaged by bars sliding).

With respect to the ‘extreme’ case, it can be observed that the centripetal fluxes of the thrusts arising from the VP of \( N_t \) - balanced by the counter-thrusts arising from the VP of \( N_c \) – become localised in the extreme external frame corner region and, along their short path, they can use concrete sections wider than the ones available in the case discussed before. In this way, the frame corner central region is available for the thrusts of the VP of \( N_t \) that, crossing that area (between arches 3-4 and 5-6 in Fig. 22), mutually balance

![Fig. 18. Extreme mod. ULS: VP, LP.](image1)

![Fig. 19. Extreme mod. ULS: annular TP.](image2)
themselves. Therefore, the decrease of $\Delta z$ (compared to the extreme case shown in Fig. 18), reduces the additional necessary reinforcement and the corresponding strain energy. The optimum situation, that occurs when the total invested strain energy is the minimum one, is reached at a ‘medium’ value of $\Delta z$. In Fig. 22 the paths of the thrusts applied by the double deviation of $N_c$ (however similar to the ones represented in Figs. 19 and 20) are not represented, in order to point out again the ‘solidarity’ between longitudinal compression and tensile paths.

Fig. 20. Extreme mod. ULS: diagonal TP.

Fig. 21. Extreme mod. ULS: complete STM.

Fig. 22. Optimum mod. VP of $N_t$ and LP/VP of $N_c$.

Fig. 23. Reinforcement layouts type 4 and 7: cracking patterns.

Fig. 23 allows to directly compare the cracking pattern and the STM. As mentioned in the step (8), a half-empirical verification of effects and causes can be useful both in the preliminary study of the design and in the executive verification. In the figure the annular traces of the bars sliding, the radial cracking and the longitudinal cracks in the external regions of the column and of the beam, next to the corner, can be recognised. It has to be pointed out, to this purpose, that the tested element has only a type 4 reinforcement
layout (Fig. 5) and then it does not have the reinforcement shown in Fig. 15 and in Fig. 20 that can be useful to the overall behaviour of the frame corner (Fig. 5).

CONCLUSIONS

Design objectives can be brought back to reach the pre-fixed durable and reliable performances in a single organic framework (Fig. 1). The instruments consist in the basic requirements that a structure must have. The guideline ‘procedure’ is the same both in the case of a design concerning the work general conception and in the one concerning detailing. Procedure steps listed, from (1) to (8), of the structural body State Transformations (Fig. 4), are analysed on models which have a sufficient versatility for the evolutionary character of the reality that have to simulate. The STM and the use of LPM (LP, TP e VP: Figs. 2, 3A, 3B and 20) are proposed, to give a physical meaning to members tracing. The continuous referring to the energetic phenomena interpretation helps their comprehension and synthesis. The experimental tests results, re-analysed by reinforcement design (from Fig. 12 to Fig. 22), and the comparison between the models form and the cracking patterns (Fig. 23) give the possibility of the empirical diagnosis rationalisation based on the effects observation. Eventually, LPM can be also useful at the conclusion of numerical models analyses.

REFERENCES