STIFFNESS-STRENGTH-DUCTILITY-DESIGN FOR CRESCENT SHAPED BRACES

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ABSTRACT :

As recently also recalled by Priestley in a keynote lecture given at the 1st ECEES, Geneve 2006, the emphasis on Performance-Based Seismic Design has forced a re-examination of the methodology employed in the seismic design of structures. Skipping all details, direct Displacement-Based Design of structures has opened up new possibilities for the structural engineer in terms of conceiving and dimensioning a structural system which offers optimized seismic performances. Focusing directly on the non-linear behavior of the lateral-resisting elements of a given building structure, the secant stiffness approach allows “logical choices regarding the force distribution” between different lateral-resisting elements.
This paper aims at investigating how these logical choices concerning strength, stiffness and ductility of lateral-resisting elements can be made.
In general, the lateral-resisting system of a given building structure can be seen as composed of a series of single lateral-resisting elements working together. The mechanical characterization of each component necessarily requires to capture both its elastic and inelastic behavior and can be assumed to be an elastic-perfectly plastic one, univocally identified by three independent parameters: stiffness (secant at yield point), strength and ductility. The mechanical characterization of the whole lateral-resisting system, as composed of the n lateral-resisting components working in parallel, can be directly obtained from the mechanical characterization of each single component and is therefore controlled by 3n parameters. Consequently, depending upon the type of lateral-resisting used, the structural designer is allowed to control up to 3n parameters upon which he can “act” to reach the desired seismic performance objectives.

KEYWORDS: lateral-resisting element, stiffness, strength, ductility, crescent-shaped braces

1. THE SINGLE LATERAL RESISTING ELEMENT (ELEMENTARY COMPONENT)

In general, the lateral-resisting system of a given building structure can be seen as composed of a series of single lateral-resisting elements (hereafter referred to as "lateral-resisting components", LRC), working together (the issue of how to combine each component will be discussed in the following sections). The mechanical characterization of each component (being either a shear wall, a bracing system or other) necessarily requires to capture both its elastic and inelastic behavior. Without loss of generality, the mechanical characterization of each elementary component can be assumed to be an elastic-perfectly plastic one, as represented in Fig. 1 (Paulay 1992).

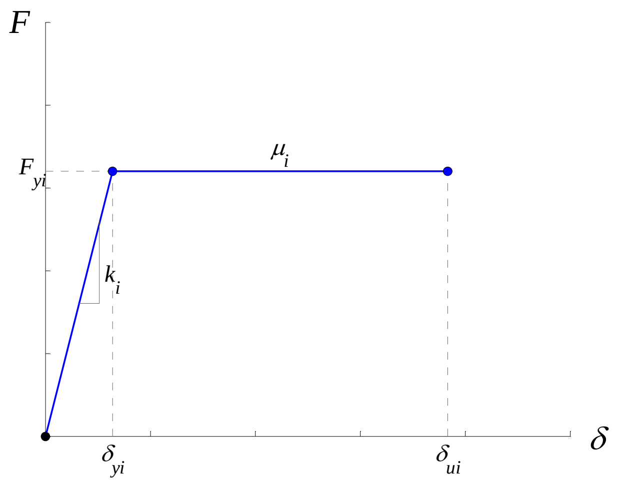

Fig. 1. $F-\delta$ constitutive law of the i-th LRC.

The following five mechanical parameters can be recognized in Fig.1:

- k_i = stiffness;
- F_{yi} = strength;
- δ_{yi} = yield displacement;
- δ_{ui} = ultimate (i.e. maximum, in terms of capacity of the element) displacement;
- μ_i = ductility.

Subscript "*i*" indicating that these quantities refer to the *i*-th LRC of the LRS.
Out of these five quantities, the independent parameters, which are necessary to fully characterize the LRC behavior, are only three. For sake of simplicity, let us assume as independent parameters the following ones:

- stiffness (secant at yield point) = the slope k_i of the idealized elastic response, i.e. the mechanical parameter which relates forces and displacements of the LRC in linear-elastic field;
- strength (or yield force) = maximum force F_{yi} which the LRC can withstand remaining approximately in linear-elastic field;
- ductility = ratio μ_i between the ultimate and the yield displacements;
- with the other two parameters derived as follows:

$$\delta_{yi} = \frac{F_{yi}}{k_i} \tag{1.1}$$

$$\delta_{ui} = \delta_{yi} \cdot \mu_i \tag{1.2}$$

2. THE LATERAL RESISTING SYSTEM OF A BUILDING STRUCTURE

Without loss of generality, let us consider plane single-degree-of-freedom (SDOF) structural systems equipped with n elementary lateral-resisting components working in parallel (which is a correct schematization under the common assumption of building structures characterized by rigid in-plane floor systems), as the illustrative ones represented in Fig. 2.

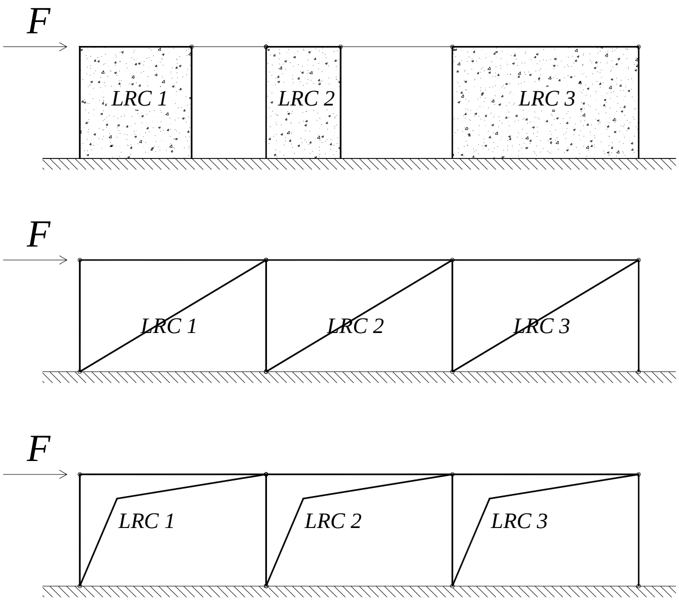

Fig. 2. Different SDOF structural systems, each one composed of three homogenous lateral-resisting components.

The mechanical characterization of the whole lateral-resisting system (hereafter referred to as LRS), as composed of the *n* lateral-resisting components working in parallel, can be directly obtained from the mechanical characterization of each single component.

Without loss of generality, let us focus on a LRS composed of three LRCs (i.e. let us assume $n = 3$). The following equations provide the relationships between the mechanical characterisation of the LRS and those of the three LRCs which make up the whole system. The LRCs are numbered progressively following the magnitude of the yield displacement: the system with the smallest yield displacement is numbered as system 1, the system with the second smallest yield displacement is numbered as system 2, and so on. Consequently, the constitutive law of the LRS is given by:

$$F = \begin{cases} K'\cdot\delta & \text{for } 0 \le \delta \le \delta_{y1} \\ K'\cdot\delta_{y1} + K''\cdot\left(\delta-\delta_{y1}\right) & \text{for } \delta_{y1} \le \delta \le \delta_{y2} \\ K'\cdot\delta_{y1} + K''\cdot\left(\delta_{y2}-\delta_{y1}\right) + K'''\cdot\left(\delta-\delta_{y2}\right) & \text{for } \delta_{y2} \le \delta \le \delta_{y3} \\ K'\cdot\delta_{y1} + K''\cdot\left(\delta_{y2}-\delta_{y1}\right) + K'''\cdot\left(\delta_{y3}-\delta_{y2}\right) & \text{for } \delta_{y3} \le \delta \le \delta_{u,LRS} \end{cases} \tag{1.3}$$

where:

$$K' = \sum_{i=1}^{n} k_i = \sum_{i=1}^{3} k_i = k_1 + k_2 + k_3 \tag{1.4}$$

$$K'' = \sum_{i=2}^{n} k_i = \sum_{i=2}^{3} k_i = k_2 + k_3 \tag{1.5}$$

$$K''' = \sum_{i=3}^{n} k_i = \sum_{i=3}^{3} k_i = k_3 \tag{1.6}$$

$$\delta_{\mathrm{u,LRS}} = \min\left(\delta_{\mathrm{u1}}, \delta_{\mathrm{u2}}, \delta_{\mathrm{u3}}\right) \tag{1.7}$$

As illustrative example of the above equations, Fig. 3 represents the mechanical characterization of the LRS composed of three LRCs.

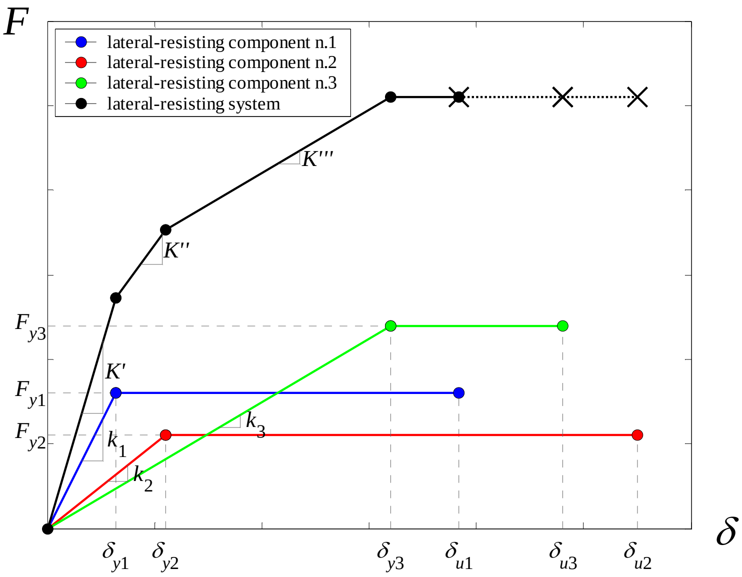

Fig. 3. $F-\delta$ constitutive law of a LRS composed of three LRCs, as obtained combining the $F-\delta$ constitutive laws of the single LRCs.

It can be observed that the overall mechanical behavior of a LRS composed of n LRCs is controlled by $3n$ parameters, given that the mechanical behavior of a single LRC is controlled by 3 parameters.
However, note that, in Fig 3, the force-displacement curve of the LRS for $\delta \geq \delta_{u1}$ is represented as a dashed line. This is because the structural system should reach collapse for $\delta = \delta_{u1} = \delta_{u,LRS} = \min\left(\delta_{u1}, \delta_{u2}, \delta_{u3}\right)$, thus diminishing the number of parameters controlling the overall mechanical behavior from 3n to $2n+1$; nonetheless also parameters $\delta_{ui} > \delta_{u,LRS}$, $\forall i$, (i.e., in the considered case: δ_{u2} and δ_{u3}) can still be the object of the characterization of the system (e.g., if it is imposed to have $\delta_{ui} \cong \delta_{u,LRS}$, $\forall i$, in order not to waste the ductility capacities of the single LRCs).
It is clear that, if certain performance objectives must be satisfied by the system, it is necessary and possible to "control" the force-displacement relationship of Eq. (1.3) and represented in Fig. 3, according to the needs/desires of the structural designer through the 3n (or $2n+1$) parameters. In theory, if all parameters are free to be controlled (section 4 investigates this issue), a LRS composed of n different LRCs can satisfy up to 3n (or $2n+1$) performance objectives (section 5 investigates this issue).

3. THE "DEGREES OF FREEDOM" AT DESIGNER'S DISPOSAL

In general, for a given LRC, the designer is allowed to "control" up to 3 mechanical parameters (k_i, F_{yi}, and μ_i) which characterize the force-displacement relationship represented in Fig. 1. Consequently, for a given LRS composed of n LRCs, the designer is allowed to "control" up to $3n$ mechanical parameters which

characterize the force-displacement relationship represented in Fig. 3.
We will refer to the free mechanical parameters, upon which the structural designer can "act" to reach desired seismic performance objectives, as "degrees of freedom" upon the LRS at designer's disposal.
In particular, depending upon the type of LRCs which are used, the designer can control either only one, or two or all three parameters. When specific elements are used to act as LRCs, it is possible to have "full control" of the mechanical behavior of the LRC (all the three parameters can be controlled) and the structural designer can impose up to 3n conditions upon the whole system behavior. On the other hand, when the LRCs work also as vertical-resisting elements (as it is the case of the shear walls investigated in (Sullivan et al 2006) and of the frames investigated in **Errore. L'origine riferimento non è stata trovata.**, etc.), the possibility for the structural designer to govern the mechanical parameters is, in general, more limited and the structural designer can impose less than 3n conditions upon the whole system behavior.
As illustrative example, it is known (Paulay 1992, Sullivan et al 2006) that, for a shear wall of given geometry (e.g., height/width ratio equal to 1:1, imposed in most cases by architectural constraints) both the yield and the ultimate displacements (δ_{yi} and δ_{ui}) are somehow fixed; therefore, two out of the three independent parameters which govern the mechanical behavior of the LRC are imposed) and the structural designer can only "act" upon the maximum force F_{yi} that the LRC can resist. In this case, the "degrees of freedom" of the LRS at designer's disposal are reduced to n and consequently his possibility to "shape" at choice the force-displacement relationship of the LRS in order to contemporarily satisfy multiple performance objectives is limited.
In summary, as given in Table 1, depending upon the number of degrees of freedom upon the LRC, the structural designer has more or less power to "govern" the mechanical characteristics of the system.

Table 1. Degrees of freedom at designer's disposal.

degrees of freedom upon the LRC $N_{dof,LRC}$	degrees of freedom upon the LRS (including imposed collapse) $N_{dof,LRS}$	degrees of freedom upon the LRS (excluding imposed collapse) $\bar{N}_{dof,LRS}$
3	3n	2n+1
2	2n	n+1
1	n	1

4. IMPOSING THE PERFORMANCE OBJECTIVES: THE ACTIVE ROLE OF THE STRUCTURAL DESIGNER

As elucidated in the previous sections, the force-displacement curve of the LRS illustrated in Fig. 3 can be modeled up to 3n points depending upon the characteristics of the LRC and its shape can be used to impose up to 3n performance objectives.
In general, performance objectives can be imposed through any suitable (estimated) response parameter (such as deformation and/or acceleration limits, either for immediate occupancy either for life-safe objectives, etc.).
This is not an easy task, given that not all performance objectives can be directly translated into mathematical conditions upon the constitutive law given by Eq. (1.3); nonetheless some interesting considerations can be readily made:

- the structural designer acquires an active role in shaping the linear and non-linear dynamic behavior of the structural system (instead of passively designing member strength according to the usual Force-Based Design approach);
- within the approach here proposed based upon the available degrees of freedom of the LRC and of the LRS, the structural engineer, before an always necessary numerical verification by means of time-history non-linear dynamic analyses of the final seismic behavior of the structure, may "guide" the overall "conceptual design" of the LRS and the "detailed design" of each LRC in such a way the structure reaches the desired performance objectives;

- the operation of imposing performance objectives through the shaping of the constitutive law given by Eq. (1.3) may lead to new design strategies (e.g., it is clear that, in order to obtain an optimized behavior of the LRS with respect to the ultimate limit state, the following condition must be satisfied by each LRC: $\delta_{ui} = \delta_{uj}$, $\forall i, j$, which may be also rewritten as: $\delta_{yi} \cdot \mu_i = \delta_{yj} \cdot \mu_j$, $\forall i, j$).

5. HOW TO IMPOSE THE PERFORMANCE OBJECTIVES THROUGH VALUES OF THE SYSTEM PARAMETERS

It's important to be noted that a performance objective (Bertero 2002) is the coupling of a seismic design level (seismic input "intensity" level) and of a performance level (state of the structure in the desired condition). In general, international codes, based on the Ultimate Limit State Methodology, refer to the three following cases (Paulay 1992, Petrini, Pinho & Calvi 2004):

- For frequent low intensity earthquake ground motions: the building functionality has to be preserved (Damage Limit State – Fully Operational). A structure has to be stiff enough to guarantee the minimum deformations and the less damages to any structural and/or non structural elements. Thus imposing a condition on the initial stiffness of the system (K_s).
- For medium intensity earthquake ground motions with a return period greater than the previous ones, some structural damages are permitted, but they cannot exceed the threshold of the economic repairing damages (Control Damage Limit State – Operational). A structure has to be resistant enough to guarantee that, in the elastic range, the minimum structural damages. Thus imposing a condition on the yielding of the system (F_{y-s})
- For high intensity earthquake ground motions with a high return period, the structure, even if subjected to severe structural and/or non structural damages, has not to collapse, preserving the whole vertical loads bearing (Ultimate Limit State). Because of the impossibility of realizing seismic structures, in terms of economic acceptability, characterized by a linear elastic behaviour when subjected to high intensity earthquake ground motions, the fundamental point of the seismic design for an Ultimate Limit State is to allow the structure to develop a plastic behaviour and to reach a certain level of damage. Consequently, the structural ductility plays the main role in the seismic design, that is the capacity of the system to develop high plastic (ultimate) deformations and appropriate dissipative capabilities, without extreme loss of strength. Thus imposing a condition on the ultimate deformation of the system (δ_{u-s}).

8. CONCLUSIONS

This paper presents an innovative approach for the seismic design of structures which, focusing directly upon the performance objectives, identifies the characteristics of the lateral (horizontal) resisting system considered completely separated (and consequently highly specialized) from the vertical one. The structural seismic performances being determined either upon strength and resistance or displacement capabilities of the lateral system, depending upon the limit state considered. The approach here introduced allows to exploit at their best both the traditional force design method and the more recent direct displacement design approach; the designer imposes/select the Stiffness, Strength, Ductility of the structure at end, in order to achieve the desired seismic performances.

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