International Journal of Civil and Structural Engineering– IJCSE
Volume 2 : Issue 1 [ISSN : 2372-3971]
Publication Date: 30 April, 2015

A Seismic-resistant Precast r.c. System equipped with Shear Link Dissipators for Residential Buildings

[Iolanda Nuzzo, Daniele Losanno, Giorgio Serino, Luis M. Bozzo Rotondo]

***Abstract*—In some areas, such as Peru or other southern American Andean countries, the combination of high seismic risk and important socio-economic development, with the consequent pressing problem of social housing, generates the need of realizing cheap, fast to execute and seismo-resistant buildings. In this view, a multistorey precast reinforced concrete structure equipped with hysteretic dissipative braces is proposed. The dissipation is ensured thanks to the employment of metallic yielding devices called shear links, allocated in steel diagonal braces, while gravity loads are supported by the precast structure. This work concerns this type of building design, performing both linear and nonlinear dynamic analysis. Particular attention is paid to the energy dissipation device modeling, with the aim of investigating its effective linear and non-linear mechanical behavior. Finally, the equivalent structural damping, provided by shear links, is evaluated through different methods suggested by American guideline FEMA 273.**

***Keywords*—seismic design; dissipation; shear link; hysteresis; nonlinearity.**

I. Introduction

High seismic risk of the southern American Andean cost [1] and the urgent problem of social housing characterizing this area justify the necessity of building cheap and seismo-resistant constructions in a short period of time. In this view, a multistory precast reinforced concrete structure equipped with dissipative braces is presented. Indeed, the industrialized prefabrication provides large volumes of construction at minimal cost thanks to its speed in producing and building process, and minor employment of material. Proposed dissipative braces are characterized by the installation of a particular metallic yielding device, called shear link, in series with a steel elastic brace. Seismic action is resisted by the dissipative braces, so that the framing structure can be designed according to gravity loads only, thus obtaining smaller dimensions of elements' cross sections and a more uniform stress distribution along them, with obvious consequent benefits.

Moreover, damage to framing elements due to strong earthquakes is prevented, avoiding expensive and invasive repairing interventions. On the other hand, the eventual substitution of the devices after a strong earthquake is easy, cheap and minimally invasive.

II. Shear Link Energy Dissipation Device

The Shear Link (SL) device (see "Fig. II-1") is an energy dissipation device suitable for seismic protection [2], [3], [4], [5], [6]. The proposed dissipator is very simple since it basically consists in a metallic plate. The main shape is obtained from a rectangular hot laminated element in structural steel, which is reduced, in some parts of it, by a milling machine. In this way, without any welded part, it is possible to obtain some “windows” of thinner thickness along the web of the device. Under shear action, milled areas yield so that plastic deformations in "windows" produce energy dissipation. Hysteretic curves from experimental tests are quite stable and characterized by low strength reduction. The milling manufacturing process [7] allows very thin dissipative areas, avoiding welding procedure. Moreover, thanks to small transversal dimensions of the milled areas, uniform energy dissipation is ensured for very low values of shear stresses, since the device requires low shear forces to yield. Consequently, it has the advantage of starting to dissipate energy at very small deformations with the potential of reducing inter-storey drifts for buildings, thus providing an important benefit for non–structural elements.

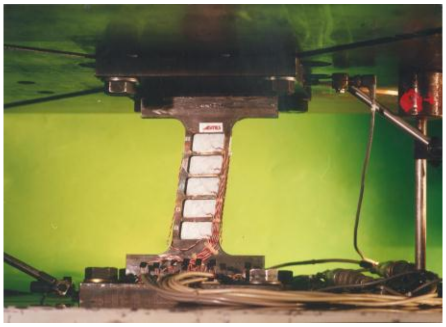

Fig. II-1 Shear link energy dissipation device

Stable hysteretic curves imply that the SL energy dissipation device must be designed so that yielding is reached before buckling of the thinner "windows" takes place, since it causes a significant reduction of the dissipative capacity [8]. For this reason these devices are usually characterized by horizontal and vertical stiffeners (corresponding to the thicker

---

Iolanda Nuzzo, Daniele Losanno, Giorgio Serino

Department of structures for engineering and architecture, University of Naples Federico II
Italy

Luis M. Bozzo Rotondo

Luis Bozzo estructuras y proyectos, S.L., Barcelona
Spain

elements of the device) between milled areas. Design of devices has to properly consider the web buckling check.

If the SL device is correctly designed, it guarantees two operating stages: before milled areas yielding, it works according to a “shear mode”, characterized by an almost linear element’s deformation, uniform shear distribution and uniform "windows" plasticization (see "Fig. II-2a"). After yielding and web buckling, the thinner parts of the device are subjected to degradation. The element behaves like a Vierendell beam and it is characterized by a typical frame deformation: this is a “bending mode” (see "Fig. II-2b"). Device continues to dissipate energy also after milled areas failure, even if its stiffness is quite reduced and so the hysteretic curves are characterized by larger displacements and lower forces than the ones proper of the “shear mode” (see "Fig. II-3"). Generally, the energy dissipation provided by the “bending mode” is not taken into account, ensuring an additional safety factor.

The SL device may be used as a link between the flexible frame and a conventional steel bracing system; in alternative, it may be used as link between flexible frames and masonry walls.

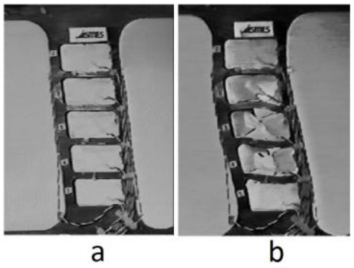

Fig. II-2 Working modes of SL device: (a) shear and (b) bending stages

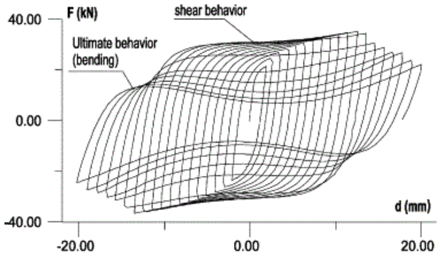

Fig. II-3 Shear link typical hysteretic curves

Designing a shear link energy dissipation device means to define several parameters, apart from steel class, i.e.: total height, dissipative height, width, thicknesses, position and dimension of stiffeners. This variability allows to obtain devices with quite different stiffness and yielding force, making them suitable for the different shear stresses expected in several points of the structure or at different stories. In order to perform a nonlinear analysis of a structure equipped with SL energy dissipation devices, their effective linear and non-linear mechanical behavior must be investigated. In this work, some simplified procedures are proposed by the authors in order to get a first sizing of the devices.

III. Structural design of a seismo-resistant precast multistorey building

In the perspective of realizing a large amount of cheap and seismo-resistant buildings in Peru for the issue of social housing, a 5-storey precast reinforced concrete structure is proposed. The building is equipped with SL energy dissipation devices, located in steel diagonal braces placed in the building corners, as depicted in "Fig. III-1" and "Fig. III-3". Beams are simply supported, so they have just to absorb gravity loads. Also columns not adjacent to braces are mainly subjected to gravity loads, while, on the contrary, all diagonals and columns next to them are heavily affected by seismic action. The geometry of the structure has been chosen in order to make the building comfortable for residential purposes, but it has also been thought to minimize the total cost. In particular, the plan of the building is 15mx20m ("Fig. III-2") with four apartments of $70m^2$ per each floor. The stairwell is around 8mx2,50m, standing in a central position.

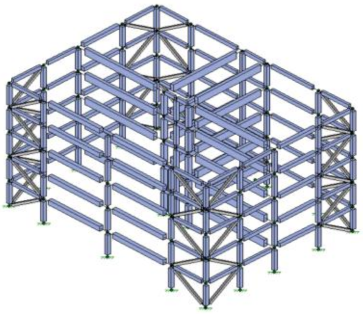

Fig. III-1 3D building's model

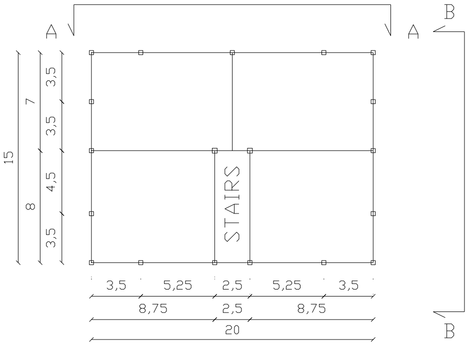

Fig. III-2 Building's plan view

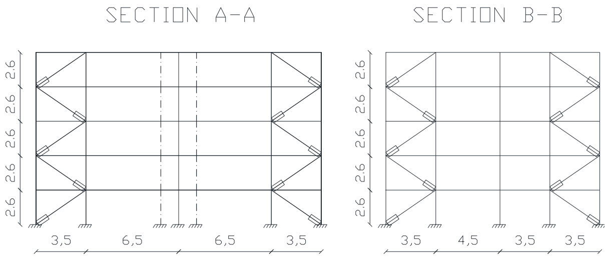

Fig. III-3 Building's longitudinal and transversal sections view

The total height of the building is around 13m, that means 2,6m for the inter-storey height. In this way the precast concrete columns have a total length of 13m and can be carried as an ordinary transport, with no additional charge. Moreover at the fourth floor duplex apartments (apartments developing along two floors) are expected, in order to avoid the elevator. In fact, according to the Peruvian law, until the fourth floor the use of the elevator is not mandatory.

The element of connection between the structure and shear links is represented by hollow steel diagonals that are allocated in the four corners of the building's plan, for a total of 40 diagonals, that also means 40 dissipators. Beams, designed for gravity loads, are characterized by cross sections that vary in a range between 65x30cm and 35x20cm. From a first step gravity loads, columns dimension is 30x30cm, with the exception of central ones, characterized by a 35x35cm cross section. For architectural considerations, diagonals are assumed with a square hollow section of 20.3x20.3cm and a thickness of 6.4mm.

At this step, preliminary sizing of the SL has been carried out by means of a linear dynamic analysis of the building. The elastic response spectrum has been reduced by the "R" factor value suggested by the Peruvian code [11] for reinforced concrete moment resisting frames (MRF). It is well known that a precast concrete building has ductile capacities quite lower than MRF structures due to its low number of static indeterminacy. The reason why, contrarily to this concept, the structure has been dimensioned considering the aforementioned R factor is that horizontal loads have to be mainly absorbed by supplemental dissipative devices, expected to be very ductile. Consequently, it is very important to guarantee a rigid connection between the structure and the energy dissipation devices, so as to ensure the transmission of seismic loads. Once structural elements and shear links have been dimensioned, a non linear dynamic analysis has been implemented in order to perform an effective check of the structural response.

The linear dynamic analysis of the structure, performed in the respect of Peruvian codes [11], [10], [9], [12], has been carried out through the commercial calculation program RISA-3D, that is packed with the most current American building codes. At this stage of design, only the elastic elements of the brace (hollow diagonals) have been modeled, hinged at both ends, while SLs have not been directly included in the model since their contribution to global ductility has been taken into account trough the approximate equivalent R factor.

The analysis output showed that columns mainly absorb vertical loads: the axial stress is the only significant one, with respect to bending moment and shear force. This happens because diagonals are horizontally much stiffer than columns and so practically carry the entire seismic action. The axial load carried out by the brace elements, $\overline{F_y}$, would represent shear forces acting on energy dissipation devices: for this reason axial stresses evaluated through the linear dynamic analysis have been employed in order to size the shear link devices. According to the distribution and the magnitude of values of $\overline{F_y}$, the need of introducing three different types of SL energy dissipators came out. Some models of the dissipative device are proposed in the following to obtain required parameters for structural nonlinear analysis.

A. Analytical model of the shear link

The approximate value of the design axial force $\overline{F_y}$ acting on braces, evaluated through linear dynamic analysis, has been set equal to the SL yielding force. Assuming that the link height and base dimensions are known from geometrical considerations, the resulting unknowns are the thicknesses of the "windows", *e*, and of the resting part of the device, *t*. Then, a system of two equations is required to evaluate the two unknowns. The dissipative brace composed by the elastic brace and the energy dissipation device, can be represented through an analytical model considering the two elements in series (see "Fig. III-4"). The diagonal stiffness k_d can be easily evaluated as

$$k_d = \frac{A_d E}{L}, \tag{1}$$

where A_d is the cross section area of the element, *E* is the material's Young modulus and *L* is the diagonal's length. The dissipative device is further simplified considering it made by two springs in parallel, corresponding respectively to the "windows", having elasto-plastic behavior, and to the thicker parts that have to remain elastic. Each window can be characterized by a stiffness

$$k_w = \frac{GA}{h}, \tag{2}$$

where *G* is the shear modulus, *A* is the cross section area of the window itself and *h* is its height, and a yielding force

$$F_w = \tau_y A. \tag{3}$$

The thicker part of the SL could be represented as a one bay, 2-storey frame whose pillars provide a total stiffness

$$k_r = \frac{48EI}{h^3}, \tag{4}$$

where *I* is the inertial moment and *h* is the inter-storey height, equal to the window's height (see "Fig. III-5").

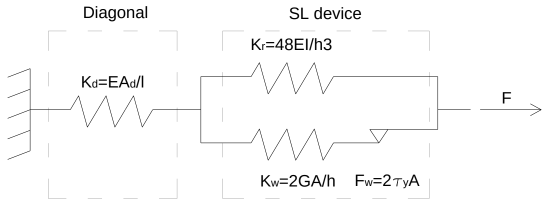

Fig. III-4 Analytical scheme of the composed system diagonal+SLdevice

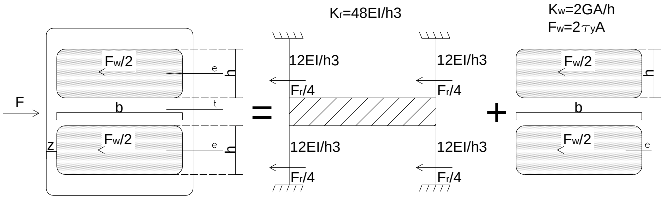

Fig. III-5 Shear link analytical model

The force F stressing a system of two springs connected in parallel is obtained by summing the forces acting in each element, while the total displacement is the same in both elements:

$$F = F_w + F_r = k_w x_w + k_r x_r = (k_w + k_r)x \tag{5}$$

and

$$x_w = x_r = x. \tag{6}$$

At the yielding point of the internal windows, the force absorbed by device rigid parts can be evaluated as

$$F_r = k_r \frac{2\tau_y A}{k_w}. \tag{7}$$

Consequently the yielding force of the shear link is given by

$$F_y = 2\tau_y A + k_r \frac{2\tau_y A}{k_w}; \tag{8}$$

this force also corresponds to the total force stressing the whole system diagonal+SLdevice, being in series. Matching the value of the yielding force with the design axial force $\overline{F_y}$ previously discussed, the first resolution equation is set. In this equation both the two unknowns, e and t, appear, respectively, in the expressions of the cross section area, A, and of the inertial moment in k_r. The second resolution equation can be obtained setting the buckling critical stress (evaluated according to state-of-art expressions) equal to twice the yielding shear stress τ_y, so as to ensure that the buckling critical stress is higher than the yielding stress. In the expression of τ_{cr} the windows thickness e appears.

$$\begin{cases} 2\tau_y A + k_r \frac{2\tau_y A}{k_w} = \overline{F}_y \\ \tau_{cr} = 2\tau_y \end{cases} \tag{9}$$

Before windows yield the equivalent stiffness of the SL is

$$k_{diss1} = \frac{F}{x} = \frac{(k_w + k_r)x}{x} = k_w + k_r; \tag{10}$$

while after yielding it reduces to

$$k_{diss2} = k_r. \tag{11}$$

Force-displacement relations of each element are shown in "Fig. III-6". It can be observed that the diagonal is characterized by an elastic behavior, while the SL device behavior is represented by a bilinear curve. Thus the equivalent stiffness of the combined system (two springs in series with a yielding point) is

$$k_{eq} = \frac{F}{x} = \frac{F}{F\left(\frac{1}{k_d} + \frac{1}{k_{diss}}\right)} = \frac{k_d k_{diss}}{k_d + k_{diss}} \tag{14}$$

where k_{diss} has to be specialized according to the force level.

The whole brace hysteretic loop is depicted in the last plot of "Fig. III-6". The yielding force remains F_y while yielding displacement of the combined system is the sum of displacements of each element at yielding.

According to this procedure, yielding force, initial and post-yielding stiffnesses of the three SL types have been obtained and are depicted in "TABLE I.

TABLE I. HYSTERESIS PARAMETERS THROUGH ANALYTICAL MODEL

Shear Link	Model	$k_{eq,1}$ [kN/m] (initial stiffness)	$k_{eq,2}$ [kN/m] (post-yielding stiffness)	F_y [kN] Yielding force
Type 1	Analytical	199394	87489	235
Type 2		193803	87489	187
Type 3		168368	47635	89

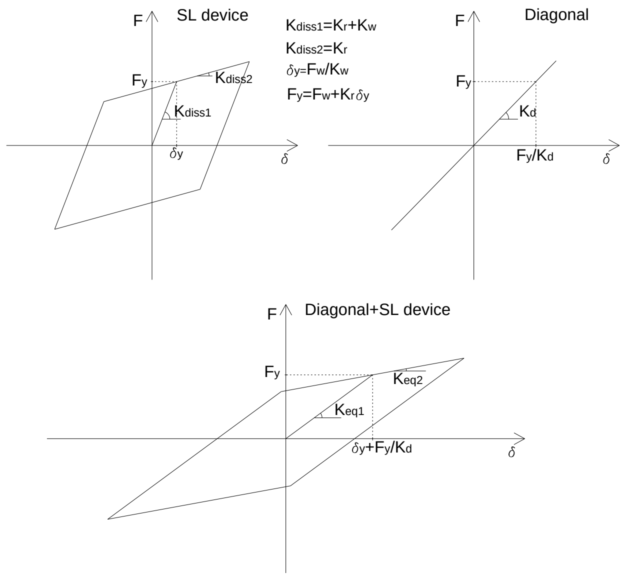

Fig. III-6 Force-displacement relations for each element in series and for the whole system

B. *Numerical models of the shear link*

Once the system "(9)" of two equations has been solved and the two unknown thicknesses have been defined, it is possible to realize a simple linear FEM model, employing shell elements, of the SL energy dissipation device, in order to study stress distribution in the device and optimize its dimensions. The model has been realized through the software RISA-3D. Stresses in shell elements can be investigated considering Von Mises stress distribution. A level of force equal to $\overline{F_y}$ should generate ideal stress in the "windows" approximately equal to its yielding stress since just the milled areas are required to undergo yielding while external parts of the device, as well as the elastic brace, should remain elastic.

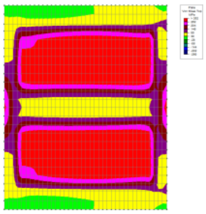

Fig. III-7 Von Mises stresses distribution in a FEM shear link model

An estimation of mechanical parameters of the SL can also be obtained through the use of a second model. This is a linear partial FEM model in which the diagonal and the dissipator, respectively represented through an analytical and a FEM linear model, can be viewed, again, as two springs working in series, subjected to the axial design force (see "Fig. III-8" and "Fig. III-9"). The diagonal stiffness k_d and the device initial and post-yielding stiffnesses, respectively $k_{diss,1}$ and $k_{diss,2}$, are estimated singularly and then combined. In this case, shear link device's $k_{diss,1}$ and $k_{diss,2}$ stiffnesses are evaluated realizing a finite elements model of it with and without its internal windows.

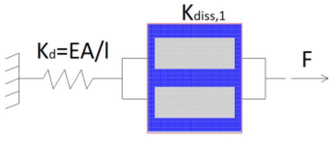

Fig. III-8 Springs working in series before "windows" yielding

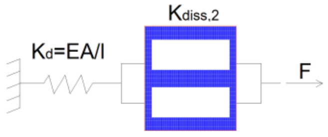

Fig. III-9 Springs working in series after "windows" yielding

Finally a third model has been adopted: it is a linear FEM complete model of the system composed by the diagonal and the energy dissipation device. Again shell elements are adopted (see "Fig. III-10").

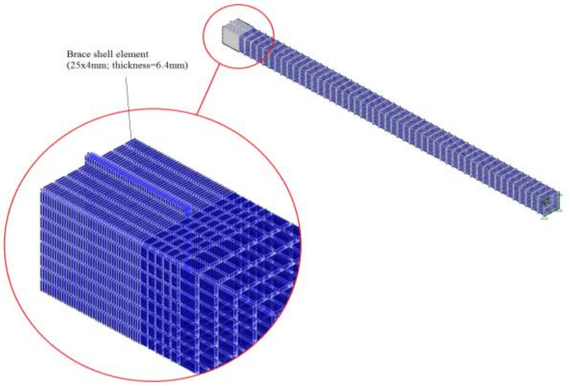

Fig. III-10 Diagonal + dissipator model

The post-yielding stiffness $k_{eq,2}$ of the system is again estimated eliminating "windows" from the initial un-yielded model.

Parameters evaluated through the two proposed numerical models are depicted in "TABLE II. Yielding force, initial and post-yielding stiffnesses evaluated through the three methods introduced above result in comparable values. The higher variance of $keq_{,2}$ values estimated through the analytical method shows the overestimation of the device's thicker part stiffness if modeled as previously explained; this also explains higher values of $k_{eq,1}$ according to the same method.

TABLE II. HYSTERESIS PARAMETERS THROUGH NUMERICAL MODELS

Shear Link	Numerical Model	$k_{eq,1}$ [kN/m] (initial stiffness)	$k_{eq,2}$ [kN/m] (post-yielding stiffness)	F_y [kN] Yielding force
Type 1	Partial FEM	188680	51698	260
	Complete FEM	179104	51246	260
Type 2	Partial FEM	181740	52159	213
	Complete FEM	174563	51757	213
Type 3	Partial FEM	148265	38845	94
	Complete FEM	146550	38164	94

Mechanical parameters obtained through the FEM complete model are considered in order to perform the nonlinear dynamic analysis.

C. *Nonlinear dynamic analysis*

Nonlinear dynamic (NLD) analysis of the structure allowed to estimate its effective performance, properly modeling energy dissipation devices. In commercial structural software, such as SAP2000, the metallic yielding devices can be modeled using the Plastic Wen link elements, in which yielding force, initial and post-yielding stiffnesses are required as input data. Eight real seismic records from the Peruvian catalogue were loaded in SAP2000 as input functions. According to the Peruvian code E.030, seismic records must be at least five and must be normalized so that the maximum acceleration corresponds to the maximum value expected at the site, i.e. 0,4g. In the Peruvian seismic design code there are no indications about the spectrum compatibility issue, that is an important topic according to Italian and European codes. Indeed, it is fundamental to choose an appropriate selection of seismic records as input, relating them to the seismic hazard of the site. Response spectra corresponding to each considered seismic event have been plotted in order to output the average of them and compare it with the elastic response spectrum: the average response spectrum results quite lower than the latter (see "Fig. III-11"). This means that available seismic records are not well representative of the seismicity of the site.

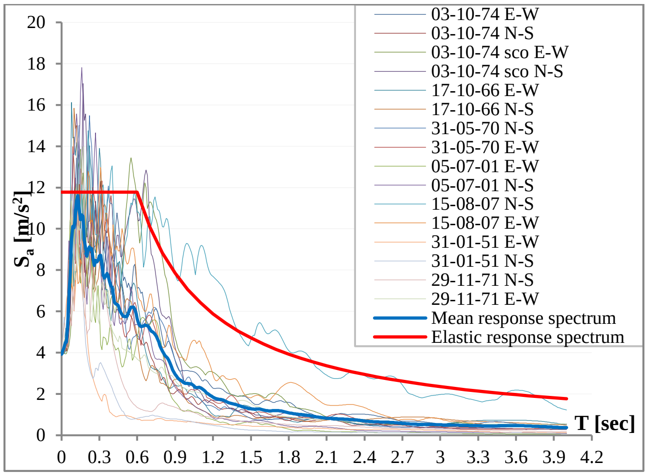

Fig. III-11 Ground motions response spectra

Under the action of ground motions, shear links exhibited an effective hysteretic behavior, as depicted in "Fig. III-12" .

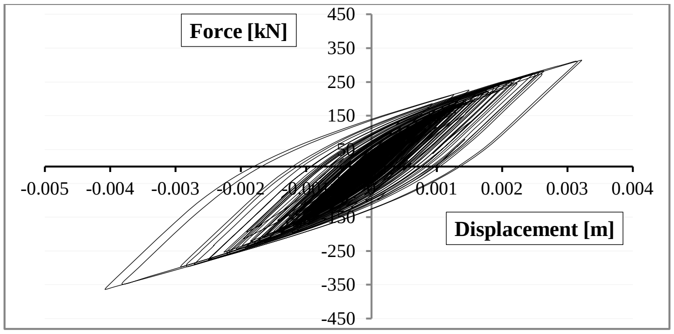

Fig. III-12 Hysteretic loop in shear link device at first floor, under the seismic event 03/10/1974

Axial force and bending moment on columns next to braces evaluated through non linear analysis, exceeded section capacity evaluated with steel reinforcement provided by linear dynamic analysis. In order to increase strength to minimum requirement, it has been necessary to increase internal reinforcement of 146%. Central columns strength and braces buckling checks were still satisfied. The average of absolute maximum joints displacements and inter-storey drifts is depicted in "TABLE III. ": the displacement check according to the Peruvian code was satisfied.

TABLE III. AVERAGE MAXIMUM JOINTS DISPLACEMENTS AND AVERAGE MAXIMUM INTERSTOREY DRIFTS

DIRECTION 1				
FLOOR	MAX U_1 [m]	MAX ΔU_1 [m]	$\Delta U_1/h_{int}$ [-]	Check
5	0.059	0.010	0.00372	<0.007
4	0.049	0.011	0.00412	<0.007
3	0.039	0.013	0.00491	<0.007
2	0.026	0.015	0.00573	<0.007
1	0.011	0.011	0.00428	<0.007

DIRECTION 2				
FLOOR	**MAX U_2 [m]**	**MAX ΔU_2 [m]**	**$\Delta U_2/h_{int}$ [-]**	**Check**
5	0.057	0.009	0.00364	<0.007
4	0.047	0.010	0.00397	<0.007
3	0.037	0.012	0.00469	<0.007
2	0.025	0.014	0.00543	<0.007
1	0.011	0.011	0.00415	<0.007

Finally, an attempt has been made to define the effective damping ratio ξ_{eff} of the building under the design seismic action. The ξ_{eff} was defined through the implementation of two different iterative methods suggested by the American FEMA 273 [13] and FEMA 274 [14], that respectively use the linear (LSP) and nonlinear (NSP) static analysis (the last performed assuming both uniform and modal load patterns). These procedures provided, respectively, ξ_{eff} values of 17.8% and 18.8% (uniform load pattern) and 18.5% (modal load pattern).

IV. Conclusions

The present work showed how a precast reinforced concrete building frame equipped with supplemental energy dissipation devices may be adopted as structural system for strong seismic actions. Seismic performance is significantly improved thanks to special shear link devices, thus allowing to employ precast frames in high seismic risk regions with the problem of social housing. Simplified models of the device have been developed, allowing both its sizing and the definition of its nonlinear behavior. Design according to Peruvian code emphasized limits of the same code concerning with ground motion events selection in nonlinear dynamic analysis. In addition to this, FEMA procedures were adopted to estimate the effective damping provided by the SL device, resulting in the adequate value of about 20%. The determined ξ_{eff} could be useful in implementing easier and faster linear analysis, even if most accurate and less conservative results can be found by nonlinear dynamic analysis.

References

[1] J.L.Castillo Aedo, J.E. Alva Hurtado, "Peligro sísmico en el Perú", Lima 1993.

[2] X. Cahis i Carola, L.M. Bozzo Rotondo, P. Alavedra Ribot, "Desarrollo de un nuevo disipador de energía para diseño sismorresistente. Análisis numérico y validación experimental de su comportamiento", PhD thesis, Barcelona 2000.

[3] F. Hurtado Soto, L.M. Bozzo Rotondo, "Propuesta de disipador genérico "SL" para edificios y su diseño sismorresistente", PhD thesis, Barcelona 2006.

[4] F. Hurtado, L.M. Bozzo, "Numerical and experimental analysis of a shear link energy dissipator for seismic protection of buildings", 14th WCEE, Beijing-China.

[5] F. Hurtado, L.M. Bozzo, "Un disipador Shear Link (SL) generalizado para diseño sismorresistente", Hormigón y acero n°235, Primer trimestre de 2005.

[6] Cahis, X., Torres, Ll., Bozzo, L., "An innovative elasto-plastic energy dissipator for the structural and no-structural building protection", 12th World Conference on earthquake Engineering 2000; Auckland, New Zeland.

[7] Bozzo, L.M, Cahis, X. y Torres, Ll., "A shear type energy dissipator for the protection of the masonry infill walls", Proceedings of the Sixth U.S. National Conference on Earthquake Engineering 1998; Seattle, Washington.

[8] Rai, D. C. and Wallace, B. J. (1998). “Aluminium shear-links for enhanced seismic resistance”, J. Earthquake Engrg. Struct. Dyn., 27, 315-342.

[9] Norma técnica de edificación E.030: Diseño sismo resistente.

[10] Norma técnica de edificación E.020: Cargas, Istituto Nacional de Investigación y Normalización de la Vivienda - ININVI, June 1985.

[11] Proyecto de Norma técnica de edificación E.060: Concreto armado.

[12] Alejandro Muños Peláez "Fuerzas de diseño y control de desplazamietos en la norma peruana de diseño sismoresistente".

[13] NEHRP guidelines for the seismic rehabilitation of buildings, FEMA 273, October 1997.

[14] NEHRP commentary on the guidelines for the seismic rehabilitation of buildings, FEMA 274, October 1997.