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THE GAPEC SYSTEM : A NEW ASEISMIC BUILDING METHOD FOUNDED ON OLD PRINCIPLES

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SYNOPSIS

The GAPEC system is a new aseismic system of the soft-story type experimented at the Centre National de la Recherche Scientifique, (C.N.R.S.) in Marseille, France. With this system, a building is standing on energy-absorption isolators set between the first story and the basement or the soil if no basement. Large scale experiments performed on a shaking-table and designs of typical high or intermediate buildings show that using the GAPEC system divides the accelerations response, shears and overturning-moments by a factor of 5 to 8. Practical applications have begun in 1978 with three buildings fitted with the GAPEC system.

Le système GAPEC est un nouveau système antisismique du type "étage mou" expérimenté au Centre National de la Recherche Scientifique (C.N.R.S.) à Marseille France. Avec ce procédé, un immeuble repose sur des isolateurs placés entre le premier étage et les caves ou le sol si l'immeuble n'en possède pas. Des essais effectués à grande échelle sur une table vibrante et le calcul d'immeubles typiques de hauteur élevée ou moyenne montrent que l'emploi du système GAPEC divise la réponse en accélération, les efforts tranchants et les moments de renversement par un facteur de 5 à 8. Les applications pratiques ont commencé en 1978 avec trois immeubles équipés du système GAPEC.

1.- INTRODUCTION.

A new trend for earthquake - resistant structures has developed for several years, which intends to confine the seismic energy in a limited area of the structure acting as a shock absorber. In the 1930's, Martel, Green and Jacobsen presented some aspects of a flexible first story and Fintel and Khan (1968) wrote about a shock-absorbing soft story concept [1]. These authors obverved that the upper stories of many buildings submitted to strong earthquakes had suffered but small damage when the first story was flexible enough to accomodate large distorsions. In the Fintel and Khan's method, the entire building should remain within the elastic range, except the soft story which undergoes elasto-plastic behaviour. As a consequence, the building would stay in a displaced position after the quake and would have generally to be demolished.

A further step is to implement a soft perfectly elastic story so that the building remains in its original position after the seismic event. The laws of the structural dynamics show us that such a story would increase the natural periods of the buildings and decrease correspondingly the acceleration response. In another way, the recent developments of rubber technology allow us to conceive such a perfectly elastic story. This old knowledge joined to this new technology has given rise to the GAPEC system.

2.- FUNDAMENTALS OF THE GAPEC SYSTEM. (G.S.)

The GAPEC system is a new aseismic system experimented at the "Centre National de la Recherche Scientifique " (C.N.R.S.) in Marseille, France, since 1973. With the GAPEC system a building is standing on energy absorption devices called isolators and located between the first floor and the basement (fig.1). These devices consist of a laminated rubber-and-steel sandwich manufactured with a new and special design. Their main feature is a relatively high stiffness in the vertical plan and about the two horizontal principal axes of the building and a low stiffness in the horizontal plan and about the vertical axis. Transverse stiffness of the isolators is currently a hundred times less than the vertical one and two hundred times less than that of the concrete columns of the first story. They constitute a very soft and short story. Isolators have a general nonlinear elastic behaviour ; the fig.2 shows typical stress-strain compression curves which seem to agree well with the following equation :

(1) $$\sigma = G\, s\, \alpha(\alpha^2 - 3\alpha + 3)/(1 - \alpha)^2$$

where

(2) $$s = 1 + 0.103\,(a/e_0)^2$$

G is the shear-modulus of rubber, a the side or diameter of the cross-section of rubber and e_0 the thickness of a rubber-layer.

Fo tall buildings, the transverse flexibility of the isolators can introduce some discomfort to the occupants under wind action. For this reason simple mechanical devices called wind-stabilizers inserted at the same level as the isolators are designed to fix the building against ordinary wind loads. When the base shear reaches a minimum designed value, the wind-stabilizers are automatically disconnected from the structure which becomes free on the isolators. After the earthquake, the wind-stabilizers are easily re-connected to the building.

3.- HIGH EFFICIENCY OF THE GAPEC SYSTEM.

The GAPEC system allows engineers to control three essential parameters of the behaviour of a building submitted to an earthquake shock, which are the lateral, vertical and torsional responses.

3.1.- Lateral response.

Due to their low stiffness, the isolators act mainly in the horizontal plane as low-pass filters by increasing the natural periods of the building. As we know, the maximum response of a structure to a ground acceleration a(t) can be found by response spectrum analysis ; thus the maximum absolute acceleration-vector is written as :

(3) $$X(t) = \sum_j \gamma_j x_j Saj$$

where

(4) $$Saj = \omega_j \left| \int_0^t a(\tau) \exp.[-\xi_j \omega_j (t - \tau)] \sin\omega_j (t - \tau) d\tau \right|_{max}$$

represents the spectral acceleration in the j th mode x_j and γ_j , ω_j and ξ_j are respectively the modal participation factor, the natural circular frequency and the equivalent viscous damping ratio of the j th mode. A typical acceleration-response spectrum is shown on the fig.3 and we can see that increasing the natural period above 2s results in a large decrease of the horizontal response acceleration. Numerous experiments were performed on the shaking-table of the Laboratory of Mechanics and Acoustics of the C.N.R.S. in Marseille with a 20-story scale model measuring 1.20m x 0.68m in plan ; height is 3.10m and weight 9 380 N ; it is excited by the 1952 Taft California earthquake, N21 E component, normally to the longer side with a maximum ground acceleration of 0.1 g. The table 1 shows the maximum measured values with and without isolators ; we can see that using the GAPEC system in the scale model divides the accelerations, shears and overturning moments by a factor of more than 8. In addition, some typical buildings were designed using the normal mode method with a complete history of the response and the design values found confirm well the excellence of the new system. For example, the fig.4 shows the designed values of the Enaluf Building in Managua, Nicaragua, which was badly damaged by the earthquake of December 23, 1972 ; the design was performed with and without the GAPEC system and we can see on the fig.4 that (a) the first predominant mode shape of the building fitted with G.S. is practically a straight line almost parallel to the undeflected vertical axis (fig.4a) ; this means, in fact, that the building moves on the isolators like a quasi-rigid body with a very small overall-bending (b) the acceleration response, shears and overturning moments are reduced by a factor of 5 at least when using G.S. (fig.4b,c,d) ; let us emphasize right now that a so large decrease of the overturning moments (fig.4d) will increase the foundation stability proportionally. In this case, the first natural period has grown from 0.86s without G.S. to 3.1s with G.S.. The design shows obviously that the Enaluf Building would have withstood the December 23, 1972 earthquake shock with light damage only if it had been fitted with the GAPEC system. Similar conclusions arise from the design of other building types. The table 2 shows the maximum design values of a typical 20-story building measuring 23.60m x 23.60m in plan excited by the 1940 El Centro California earthquake. N-S component ; we see that, in this case, using GAPEC system divides the acceleration response, shears and overturning moments by more than 8. The fundamental period has grown in this case from 1.15s without G.S. to 5s with G.S..

3.2.- Vertical response.

In the vertical plane the isolators act mainly as dampers with a loss factor of 0.1. Their relatively high vertical stiffness involves a large decrease of the P - Δ effect in the structure and explains the lateral quasi-rigid motion that we mentioned above.

3.3.- Torsional response.

The torsional stiffness of the isolators is currently 2,000 times less than that of the concrete columns of the first story. Consequently the buildings fitted with G.S. also have a very low torsional response acceleration.

4.- THE MAIN ADVANTAGES OF THE GAPEC SYSTEM.

Examining the current aseismic technics, we can see that the GAPEC system has four main advantages related to the foundation stability, safety of the structural and non-structural elements and building coast. We shall discuss these points successively.

4.1.- Foundation stability.

The large overturning moments induced by strong earthquakes in classical aseismic buildings involve an important rocking of the base with high compression stresses in the soil foundation and sometimes alternative states of tension and compression. Large irregular settling can occur resulting in big damage for the structure. As we have seen in the last section, the GAPEC system strongly reduces the shears and overturning moments and consequently decreases the base rocking proportionally. The soil foundation remains reasonably strained during the earthquake and no or little settling is observed. G.S. confers in fact to the building what is certainly the most important parameter of safety, e. g. the base stability.

4.2.- Safety of structural elements.

It is well known [2] that the current aseismic designs are based upon the concept that a structure must be able to resist moderate earthquakes with minor structural and some non-structural damage and resist major catastrophe earthquakes without collapse, but with permissible major structural and non-structural damage. In the best case, this means much expensive repairs and often a complete demolition of the building. The conditions are obviously quite different if the structure is fitted with G.S. Indeed, the large decrease of the seismic forces involves that the structural elements undergo moderate strain only and the building suffers no or minor easily repaired structural damage when undergoing a large earthquake. Moreover, in case of successive shocks, due to the elastic properties of isolators, the building fitted with G.S. perfectly recovers its initial position after each shock and remains quite able to resist the next one.

4.3.- Safety of non-structural elements.

Overall-bending and relative displacements between adjacent floors of classical aseismic buildings are important during strong earthquakes. The non-structural elements are generally unable to accommodate these differential motions and suffer damage usually beyond repair. We have seen in the first section that a building fitted with G.S. behaves nearly like a rigid body ; as a consequence, overall-bending and relative displacements between adjacent floors are reduced to a degree more easily accommodated by non-structural elements which suffer no or small damage. If, as stated in [3], the skeleton in tall buildings is only 20% of the total coast, the high safety given by G.S. to the non-structural elements represents very large savings of money.

4.4.- Building coast.

The general decrease of shears and overturning moments of a building fitted with G.S. results in substantial savings in the size of the structural elements, chiefly in foundation. These savings balance the coast of the devices of G.S. for a protection against moderate earthquakes. For strong earthquakes, the use of G.S. can introduce a few additionnal per-cents on the coast of the classical aseismic building, depending on the type of building and the country where it is located. However, in view of the fact that, after an earthquake, the building remains in use without important repairs. G.S. is undoubtedly much cheaper than any of the present classical aseismic systems.

5.- THREE BUILDINGS FITTED WITH G.S.

The practical applications of G.S. have begun in 1978 by three buildings located at Saint-Martin de Castillon, near the little town of Apt in the french department of Vaucluse. This is a seismic area classified 2 in the "Règles Parasismiques 1969" which are the french aseismic regulations.

The first building is a dwelling-house, the second one is for technical purposes and the third one a recording studio ; they are spaced of 14cm one from the other with adequate flexible passages between them. They are fitted by 200mm diameter isolators designed and supplied by the company E.R.A. of Marseille [4]. The table 3 shows the physical caracteristics of these buildings. They were designed for a VIII M.M. earthquake according to the french aseismic regulations. The table 4 shows the results of the design performed with and without G.S. ; the comparison is made in the X direction, but we have to notice that the results are practically the same in both directions when the buildings are fitted with G.S. We can see on the table 4 that G.S. applied to low buildings divides the base shear and overturning moments approximatively by 2 ; which is again very satisfying. We observe that the natural periods are increased, in this case, by a factor of about 30.

The coast of the isolators was 7% of the structural works, of which 2% have to be taken off for the savings on the structure resulting of the decrease of seismic forces. The extra-coast was thus 5% of the structural works, which is low for a protection against earthquakes, specially in view of the high amount of additionnal savety brought by the system.

6.- CONCLUSION.

Based on old principles, the GAPEC system results of the large improvements made in the rubber technology. It represents presently one of the most efficient way to protect buildings fully against earthquake risk at very reasonable coast.

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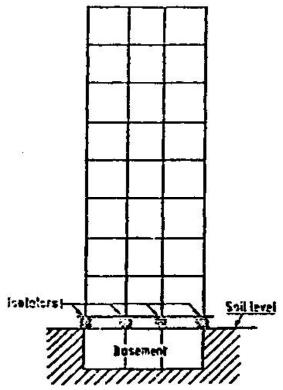

Fig.1. The GAPEC SYSTEM

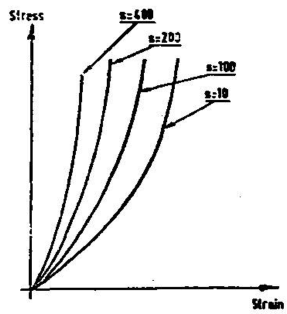

Fig.2. Typical stress-strain compression curves of isolators.

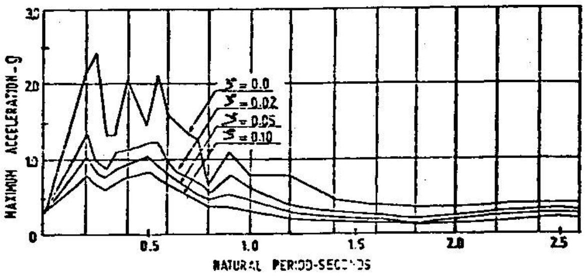

Fig. 3. 1940 EL CENTRO California Earthquake, N.S component. Acceleration-response spectra with values of damping ratio 0.0, 0.02, 0.05 and 0.10.

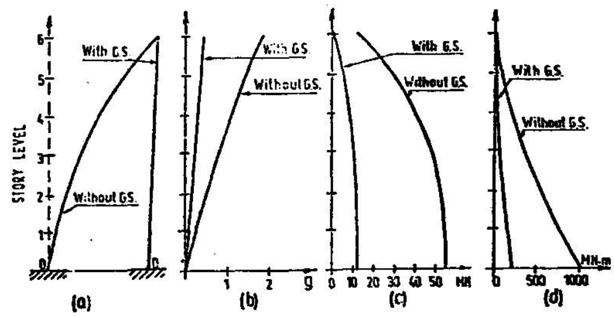

Fig. 4 – The Enaluf building in Managua, Nicaragua. Design values, North-South direction, with and without the GAPEC SYSTEM (a) 1rst predominant mode shape (b) acceleration-response; (c) shears; (d) overturning moments –

	Without G.S.	With G.S.	Ratio Without G.S. / With G.S.
MAX-Acceleration-response (g)	0.170	0.020	8.5
MAX-Shear (N)	1014	123	8.2
MAX-Overturning moment (N.m.)	1570	190	8.3

Table 1. The scale-model. Accelerations, shears and overturning moments measured with and without G.S.

	Without G.S.	With G.S.	Ratio Without G.S. / With G.S.
MAX-Acceleration-response (g)	0.28	0.032	8.7
MAX-Shear (N)	43×10^6	4.86×10^6	8.8
MAX-Overturning moment (N.m.)	1383×10^6	161×10^6	8.6

Table 2. Maximum design values of a typical 20-story building with and without G.S.

Building N°	Sizes in plan (m x m)	No of Stories	Weight (tons)	Number of 200mm isolators	Horizontal stiffness (10^4N/m)
1	13.00x13.10	2	414	21	655
2	9.60x8.20	1	121	11	343
3	9.10x9.80	1	208	10	312

TABLE 3. Main caracteristics of the first three buildings fitted with G.S.

	Building N°	1rst natural period (s)	Max. response accelera-tion (g)	Max. shear (10^3N)	Max. overturning moment (10^3N.m)
Without G.S.	1	0.063	0.100	414	1536
With G.S.		1.58	0.055	228	728
Ratio		0.04	1.82	1.82	2.11
Without G.S.	2	0.031	0.100	121	220
With G.S.		1.18	0.063	76	101
Ratio		0.03	1.59	1.59	2.18
Without G.S.	3	0.057	0.100	208	568
With G.S.		1.62	0.055	114	285
Ratio		0.03	1.82	1.82	1.99

Table 4. Seismic design of the three buildings with and without G.S.