Strategies for the protection from structural failures under seismic events

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***Abstract*—**In the paper one presents some researches in course of development in the field of protection of new and existing structures subject to dynamic events. The described researches involve both theoretical, numerical and experimental features on the topic.

Design issues for base isolation systems are reported, as well as the dynamic behavior of some structures that can be modeled under monolithic rigid mode and multi-storey steel frames are presented, and the coupling with some control devices is investigated. As concerns the rigid blocks, pure rocking motion is analysed and the response attenuation is accomplished by means of dampers introducing a dissipative liquid mass. In the case of the steel frame, the mitigation of the dynamic response is pursued by means of a base isolation system, able to get a significant reductions of dynamic response variables. Reinforcement techniques for existing buildings based on composite technology are referred to in the final part of the paper, with special regards to new composites with cement matrix.

***Keywords*—** Structural Dynamics, Dynamic Control, Refurbishment Techniques, Seismic Event..

I. Introduction

THE protection of new and existing constructions subject to dynamic phenomena represents a basic issue for the international scientific community.

This research interest mainly relies upon the need of preserving existing structures and infrastructure or the new ones from damages caused by earthquakes, that may result even in the global collapse of the structure or give rise to local crises of parts of the structure.

Minor damages refer to decrease or loss of serviceability of the structure after the event, and disease/malfunctions during the occurring of the event because of significant displacements/accelerations, exceeding some thresholds.

The problem is deeply felt because of the wide seismic areas characterized by high earthquake hazard, distributed all over the world.

Additionally, the significant seismic risk in some geographic regions often superposes to an high vulnerability of the structures in the area to seismic events.

The last decades witness a large effort both from the scientists and from the factory, for developing a variety of systems, devices, technologies, reinforcement techniques devoted to increase the degree of prevention of structural damages against strong motions in civil structures.

Also infra-structural systems and constructions with monumental/artistic/historical value, besides other class of special objects requiring preservation against dynamic motion, such as artistic objects in museums, statues, ancient columns, electrical equipments and so on have been attracting special attention for preserving their integrity.

Approaches to the problem of attenuation of the structural response vary from the set up of control devices for reducing the structural vibrations [1]-[7] to the development of reinforcement techniques, also involving new composite materials for increasing the dynamic strength of the structure, which is particularly significant for existing historical structures [8]-[13].

Under the theoretical profile, they include the set up of analytic methods for the development of control algorithms and the compensation of errors and noises possibly occurring in active control systems, as well as the design of control systems, actuating and sensing devices, also with reference to semi-active systems founded on the adoption of special smart materials, and coupling of passive or semi-active systems with active systems in integrated hybrid systems.

With reference to composite reinforcements, they are mainly preferred in existing or ancient constructions [14]-[29].

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To this regard, theoretical and numerical tools have been developed for the set up and analysis of the mechanical model of the composite material and body, and its coupling with the structural material, as well as for the analysis and forecast of the unreinforced and reinforced structure, and the design of the reinforcement provision and the identification of the areas needing the adoption of the reinforcement [8]-[13].

On the other side, experimental investigations have been widely developed on structures scaled from the small dimension up to full/real scale case, setting up laboratory facilities and machines, such as shaking tables, as well as instruments for the real scale tests to be used in situ.

New trends in this field mainly rely upon the exploitation of new composite materials, also based on the adoption of cement matrixes.

In the following one presents some researches in course of execution on the subject.

II. BI SYSTEMS FOR THE MITIGATION OF STRUCTURAL DYNAMICS

II.1 About BI Systems

An effective approach for the mitigation of structural vibrations may consist of introducing at the foundation level of the structure a properly designed Base Isolation (BI) control system.

The design stage is referred to the double task of moving the frequency range mainly characterizing the incoming seismic excitation far from the range of interaction with the dominant frequencies that rule the response of the structure on one side, and of reducing the energetic transmission of the dynamic input, by realizing a damping filter and interrupting the continuity between the surface layers of the soils and the foundation of the structure.

The performance of base-isolation devices (for state-of-the-art review on base isolation of structures one may refer to Kelly [1], [2] and Jangid and Datta [3]) in mitigating inertia forces due to intense earthquakes thus strongly depends on the proper calibration of the isolator own frequency, that should be carefully dimensioned taking into account both the dynamical characteristics of the superstructure and the frequency content of the expected disturbance.

II.2 A BI System Based on Soil Properties at Site

At the University of “Naples Federico II”, a BI design approach has been developed for optimally tuning the parameters of a seismic isolation device accounting for either the structure dynamic characters or the ground input expected macro-properties.

The control system is designed in the frequency domain by setting up a procedure able to take into account the influence of sub-soil mechanical properties on the performance of base-isolation system itself.

In the approach one measures the energy transmitted to the superstructure, compared to the energy filtered by the isolator, by the cross/auto correlation functions of the response degrees of freedom, that are presented in closed-form. This allows to prevent gross errors in the energy evaluation, calculated by integration of the spectral density functions.

The final optimum problem is then set up searching for the optimal isolator parameters (denoted by m_1, k_1 and c_1), depending on the properties of the soil at the site (η and ξ).

The objective is to minimize the energy introduced in the structure $\mathcal{E}_{str}$ by the dynamic excitation, while allowing a bounded energy absorption in the isolator $\mathcal{E}_{is}$, to be kept lower than a prefixed threshold $\overline{\mathcal{E}}_{is}$, as follows

$$\begin{cases} \text{Find} \quad \min\limits_{m_1,k_1,c_1} \mathcal{E}_{str}\left(m_1,k_1,c_1 \mid \eta,\xi\right) \\ \text{Sub} \quad \mathcal{E}_{is}\left(m_1,k_1,c_1 \mid \eta,\xi\right) \le \overline{\mathcal{E}}_{is} \end{cases} \tag{1}$$

II.3 An Improved BI System

Further improvement of the performance of the base-isolation designed taking into account the soil/structure interaction may be obtained by turning the passive isolator into an hybrid one.

This is accomplished by coupling the passive isolator with an active vibration device able to produce an active force counteracting the incoming excitation.

Even in this case the proposed approach is based on the set up of a constrained optimum problem, where the control parameters of the active device should be carefully tuned in order to get the best performance of the hybrid combined system.

The proposed control algorithm essentially operates a frequency decomposition of the forcing action and is, therefore, developed in the frequency domain.

After the preliminary frequency analysis of the structure providing the expressions of the passively and actively controlled response gain functions (in this case depending on the control parameters), the optimum problem is set up in order to activate the control force only on some specific frequency ranges of interest.

By considering an active isolation device able to infer an active force counteracting the incoming excitation $\mathbf{f}^*(t)$ related to the ground motion $\mathbf{u}_g(t)$, an additional control force term $\mathbf{w}(t)$ should then be introduced in the dynamic equilibrium equation in absolute displacement terms as follows

$$\mathbf{M}\ddot{\mathbf{y}}(t)+\mathbf{C}\dot{\mathbf{y}}(t)+\mathbf{K}\mathbf{y}(t)+\mathbf{w}(t)=\mathbf{C}\dot{\mathbf{u}}_g(t)+\mathbf{K}\mathbf{u}_g(t)=\mathbf{f}^*(t) \tag{2}$$

where $\mathbf{y}(t)$ denotes the absolute displacements vector, superimposed dots denote first and second time derivatives, **M**, **C**, and **K** denote the mass, damping and stiffness matrices respectively.

The only non-zero element $w_1(t)$ of the control vector $\mathbf{w}(t)$ concerns the (first) isolated floor.

The control force may be assumed as based on a derivative feedback, with q(ω) the control coefficient to be designed as function of the frequency ω in the frequency domain, related to absolute velocities, in the form

$$\mathbf{w}(\omega,t)=q(\omega)\mathbf{B}\dot{\mathbf{y}}(t) \quad (3)$$

with **B** the matrix governing the distribution of the control action over the structure.

Eq.(3) expresses the condition that the control force is composed by control frequency contributions, each one optimized at the specific frequency.

The design strategy, at this stage, may be set up with the objective of optimizing the control parameter of the active vibration device to be coupled to the already designed passive base isolation system.

The definition of the control parameter q(ω) can be pursued by solving a suitably set up optimum problem, for example defined in the frequency domain.

A possible strategy may consists of minimizing the employed control force for any of the harmonic components of the incoming excitation; in the same time one may require that the isolator absolute acceleration is kept under a prefixed percentage (defined by means of the function $\alpha(\omega)\in[0,1]$) of the uncontrolled isolator acceleration.

In this case, after some developments, one may get the final closed form expression of the controlled parameter q(ω), which is optimal for any harmonic component of the forcing action.

Once the optimal control parameter for the real system has been determined, one can define the overall control action.

For a generic bounded-support forcing function (like in case of seismic action) the control force can be expressed as

$$w(t)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty} q(\omega)\dot{y}_1(\omega,t)d\omega \quad (4)$$

and, then, its instantaneous definition requires the instantaneous frequency decomposition of the structural response.

The numerical investigation developed on a 5-storey shear-frame structure subject to a white noise base acceleration with zero mean and unitary variance, scaled in such a manner to have a peak acceleration of 0.4g, with the first floor coinciding with the BI-level, shows the effectiveness of the hybrid system with comparison to the passive one.

In Fig. 1 and Fig.2 one reports the drift diagrams vs the time variable referred to the BI floor and to the 3^{rd}-4^{th} floors respectively, showing the significant response reduction for the coupled optimized control system.

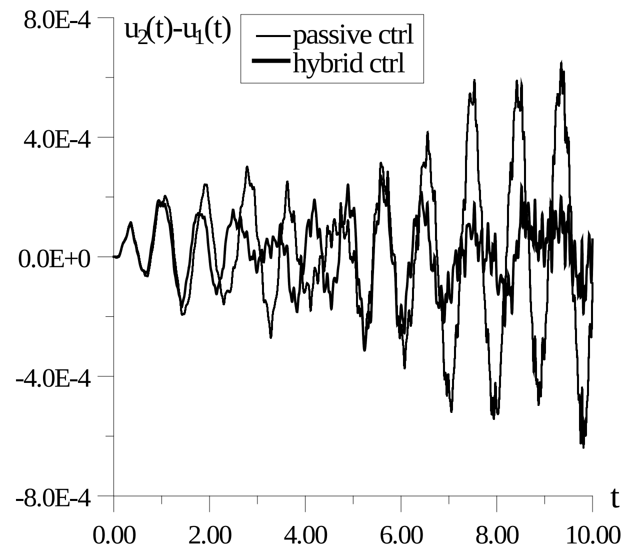

Fig.1- Inter-storey drifts of the super-structure with the passive or hybrid BI device at the isolation level.

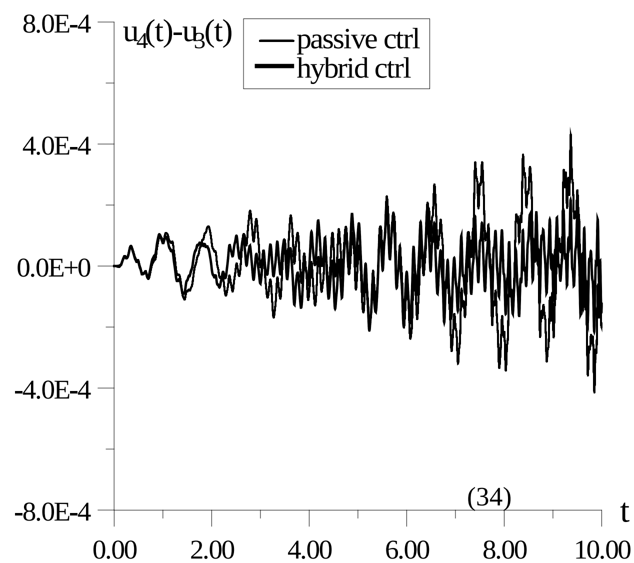

Fig.2- Inter-storey drifts of the super-structure with the passive or hybrid (γ=1/60) isolation device.

In conclusion, the results of the numerical investigation seem to show a very good performance of the hybrid system with comparison to the simple passive isolation device, especially, because it employs very low energy attaining maximum values of the forcing function approximately equal to almost 1/30 of the maximum intensity reached by the occurring excitation.

III. TLD DEVICES FOR THE ATTENUATION OF STRUCTURAL DYNAMICS

III.1 About …..

The attachment of additional masses to the main structure with the objective of dissipating the energy supplied by the dynamic event and counteracting the incoming dynamic forces is a well known control approach.

Even in its passive mode it may give appreciable results in terms of attenuation of the structural vibration with a null control energy supply, once properly tuned the properties of the mass with reference to the characteristics of the structure.

When adopting sloshing masses, based on the energy dissipation through the liquid mass motion in suitably shaped tanks, high damping capacity may be conferred to the structure.

This strategy may be applied in order to reduce vibrations occurring also in special structures, monolithically rocking under ground motion.

This special class of structures, modeling a wide variety of objects subject to dynamic motion, is affected in its response by the non-linearity typical of the relevant kinetic mode which is unilateral and embeds the impacts at the pivotal points, and by the random character of the response itself.

This latter feature, superposed to the uncertainty relevant to the excitation itself (its distribution and intensity at the site [30]-[31]), make forecasts very difficult to be performed and pushes towards the adoption of worst scenario approaches [32]-[34].

III.2 Laboratory tests on structural prototypes with TLDs

Some experimental tests have been executed At the University of Naples “Federico II” on rigid blocks equipped or not with some liquid sloshing devices, demonstrating that the adoption of the Tuned Liquid Dampers (TLD), and their proper tuning, may lead to satisfactory results.

Actually the need of predicting and preventing failures associated to rocking and overturning of rigid structures undergoing strong ground shaking have motivated a consistent number of studies on rocking response.

Therefore the possibility of coupling some sloshing devices to rigid blocks for attenuating their response to dynamic excitations appears of main interest.

To this regard, some experimental tests have been developed on a unidirectional shaking table moving in the horizontal direction for simulating the dynamic motion.

The shaking table is an MTS system and is automatically connected to a system which both gives the input signal to the table and records the output signal.

The dynamic experiments have been executed on block models moving under pure rocking. The rocking motion is affected by very complex dynamics as mentioned in the above, that push towards the adoption of worst scenario approaches for vulnerability assessment that increase the robustness of forecasts.

Fig.3– Sample of dynamic tests on purely rocking blocks equipped with a rectangular TLD, fixed on the top.

Fig.4 – Sample of dynamic tests on purely rocking blocks equipped with a trapezoidal TLD, fixed on the top.

The experiments were executed keeping a fixed span and varying the frequency of the harmonic base-excitation inferred by the shaking table, and using different span values.

The first experimental campaign was developed on blocks, both having various sizes and geometric dimensions’ ratios (thickness/height), made of thin aluminum plates, and subject to pure rocking motion around its base edges.

At the second stage, an experimental investigation on the blocks coupled with a number of sloshing devices with different geometries, shapes and liquid ratios was developed (Figs 3 and 4).

Collected data from tests allow to show the potential of the strategy even in this case and to relate the response reduction to the liquid amount in the tanks and tank shape, as clear from the sample test diagramed in Fig.5.

Comparison between the various liquid depth levels reveal the potential efficiency of the liquid damper system in attenuating the vibrations of the structural model. Looking at the results of the experimentation, some basic features can be outlined.

The overall benefit by the liquid damper does not appear to be homogeneous on the frequency range, but it is dependent on the frequencies at which the power of the excitation is lumped. In particular the benefit it is much higher in some frequency range which also depends of the geometrical/inertial properties of the structure under observation.

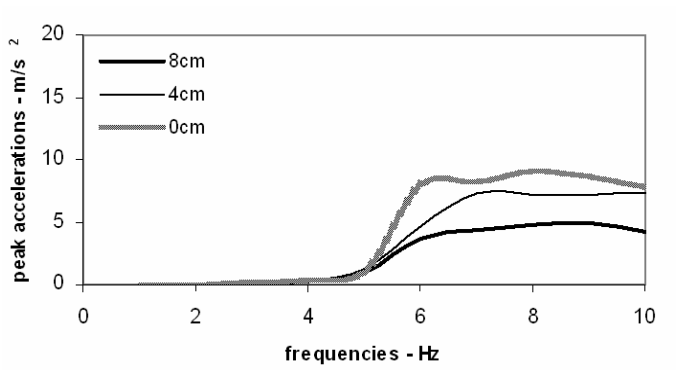

Fig.5 – Sample of data relevant to the block 30x30 in the cases of a not-activated sloshing mass (0 cm of liquid) and of an activated trapezoidal sloshing mass (4 or 8 cm of liquid).

Moreover the design of the liquid damper (the liquid mass and the shape of the tank) is fundamental for the performance of the device.

In all the tests the benefit potentially appears very significant.

Finally the device should be carefully designed, keeping into account both the excitation's character and the object's inertial properties.

IV. The Protection of Existing Structures Based on New Reinforcement Techniques

When dealing with existing structures, and, in particular, when referring to historical and monumental constructions usually made of masonry material, current reinforcement techniques are often based on the adoption of composite materials, which offer a number of benefits with respect to traditional intervention techniques, and are able, to increase the resistance of the structures even as regards dynamic events.

In the field of Civil Engineering therefore in the last decades the spread out of Fiber Reinforced Polymers (FRP) for structural applications has been significant, because of the main characteristic of these materials that is the high tensile strength.

This type of reinforcement has been widely used in the restoration of damaged structures, as well as for the static retrofitting of structures built in seismic areas, also because of some other advantages such as their extreme lightness, reversibility of the provision, easiness about their implementation/application with low costs and without the use of any special equipment, as well as the positioning times.

Based on this experience, there is currently a large interest of the international scientific community in considering new composite materials, and a related increasing use of methods of structural reinforcement is recorded for existing structures by adopting new composite materials.

In the new generation of the reinforcements, one may distinguish the following types of composites, among others:

- FRCM (Fiber Reinforced Cementitious Matrix)
- TRM (Textile Reinforced Mortars)
- SRG (Steel Reinforced Groot)

The cement matrix, which is inorganic, allows the adhesion, and plays four basic roles:

- binder (it ensures the maintenance of the shape of the reinforcement);
- bonding agent (it preserves the correct adhesion between the reinforced element and the reinforcement);
- protection (it protects fiber from physical and mechanical attacks);
- transfer (it transfers the forces from the reinforced structural element to the reinforcement and it equalizes forces between fibers).

The mechanical characteristics of the matrix are decidedly inferior to those of the fibers, but their union achieves a perfect combination of strength and durability, in addition to ensuring the function for which the reinforcement is designed.

In particular, the behavior of the "Fiber Reinforced Cement Matrix Composites" (FRCM), as a new type of composite materials exploitable for structural applications which introduces an innovation in the field of structural reinforcement systems denominated FRP (Fiber Reinforced Polymers), with an inorganic cement instead of the more common epoxy, is actually under analysis, as regards the evaluation of the load capacity, the understanding of the mechanism of failure in such systems, and the strain development and distribution during mechanical testing.

From the experimental investigations on masonry walls reinforced with FRCM [35]-[36], it is evident that the new system of structural reinforcement FRCM, unlike FRP, employs an inorganic matrix which is perfectly compatible under several features (chemical, physical and mechanical) with the support. With particular reference to the walls, the reinforcement FRCM has considerable advantages compared to conventional FRP:

- Fire resistance identical to that of the substrate (concrete or masonry): FRP systems lose their structural properties during a fire due to poor heat resistance of the resins used to make solid the fibers. It is well known that the resins (polyester and epoxy) lose their structural characteristics at temperatures between 80 and 150 ° C.

☐ Permeability comparable to the walls: The system FRCM enables normal thermo-hygrometric exchanges with the outside, while an epoxy resin which, by definition, is a closed-pore polymer, thus eliminates this possibility. This means that the moisture present in the masonry cannot freely escape and migrate towards the outside.

☐ Applicability on wet: on the contrary, FRP however, can only be applied if the support is devoid of moisture, as resins (polyester and epoxy) do not catalyze in the presence of water.

☐ Easy application even on rough surfaces and irregular and manipulation: The layer of inorganic mortar, fills the irregularities of the surface (considered the system thickness) without the need for shaving as in applications with FRP.

V. Conclusions

In the paper one focuses on some research developed in the field of protection of civil structures subject to seismic events.

Data relevant to some laboratory and numerical tests executed on structural prototypes of rigid blocks and multi-storey steel frames subject to dynamic motion are reported with the overall strategy adopted for each case.

Results are described relevant to different approaches to the building protection, and, in particular, reference is done to the case of coupling of the main structure with some control devices for reducing the structural dynamic response.

The increasing adoption of new reinforcement composite materials and techniques for existing constructions, and especially historical and monumental is referred to as well, with comparison to more common Fiber Reinforced Polymers.

With concerns to the proposed approaches based on the dynamic control of the structural response one may figure out some conclusions.

In the case of the steel frame the numerical investigation demonstrates that the BI system may deeply mitigate the structural response, exhibiting in most cases a much more favorable behavior compared to fixed base model.

The performance of the device in its passive mode may be optimized when considering at the design stage the soil properties, and, even more, when turning the system into an hybrid one with an integrated actuation device.

On the other side, several advantages are offered by the adoption of liquid mass even for structures monolithically rocking under dynamic motion, including: low cost, easiness of installation in existing structures and effectiveness even for small-vibrations.

Laboratory tests on rigid prototypes coupled to liquid masses show that the benefit potentially appears very significant once tuned the liquid mass properties in such a way to take into account both the excitation's character and the structure's inertial properties.

Finally new frontiers of reinforcements through composite provisions for retrofitting of existing constructions even with regards to seismic solicitations, lead to further analysis of new composites based on inorganic cement matrixes.

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