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A European Association for the Control of Structures joint perspective. Recent studies in civil structural control across Europe

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SUMMARY

Structural control has been comprehensively studied over the world as a multidisciplinary research field. The present work is motivated by an attempt to give a common frame to the recent research and applications of structural control technology in civil engineering across Europe. They include novel passive dampers, functional materials and semi-active dampers, active control systems, and their performance investigations. Design methods for the vibrations reduction of buildings, bridges, and wind turbines are discussed with reference to case studies. Control algorithms and dimension reduction techniques are also studied. Adaptation strategies and techniques based on the potential offered by piezoelectricity are reviewed. Copyright © 2014 John Wiley & Sons, Ltd.

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KEY WORDS: vibrations control; seismic isolation; viscous damping; shake table tests; adjacent structures coupling; semi-active control; Bouc–Wen hysteresis; magnetorheological damper; pedestrian bridges; decentralized control; hybrid control; wireless sensors; wind turbines; adaptivity; building envelope; finite states control; impact absorption; piezoelectricity; shape control; spatial filter; compatibility filter; structural health monitoring

1. INTRODUCTION

Since 1993, the European Association for the Control of Structures (EACS) has engaged in coordinating fundamental research, tracking the innovative technological developments, promoting dissemination and international collaborations. Periodically, it is responsible for preparing an up-to-date regional report on the most recent research progress carried out in the field of structural control to be presented at international workshops. The latest one, named the Sixth International Workshop on Structural Control and Monitoring, was held in Sydney, Australia, in December 2012. It was in this occasion that several members of the association were contacted and asked for a short contribution representative of their ongoing research efforts. From the resulting report, it was possible to clearly identify some common trends, which

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covered a spectrum of structural control applications wide enough to be considered relevant, although not exhaustive. This work answers the need of extrapolating the key-innovative aspects of current research and integrating them into a common framework. The paper is structured as follows.

In Section 2, passive control systems are discussed with the focus being placed on the seismic protection of structures. Selected case studies concern emerging technologies for seismic isolation (SI) and viscous dampers for energy dissipation (ED). In Section 3, methods to investigate the possibility of tuning the damper properties by means of semi-active strategies are presented with reference to both numerical studies and practical implementations. The realization of semi-active magnetorheological (MR) dampers has received particular attention in literature as one of the most promising technologies for vibrations reduction during external excitation of different nature. Their application to pedestrian bridges is discussed as case study. Decentralized control strategies, control schemes adequate for smart base isolated systems, and vibration control strategies for wind turbines are briefly reviewed as examples of recent studies in active control algorithms targeted to the mitigation of the dynamic response of structures. In Section 4, several techniques are presented where structural adaptivity is the common crucial aspect to pursue new, challenging design objectives. The investigated tools include the finite states control strategies for adaptive building envelopes, the adaptive impact absorption systems, and piezoeletricity. Finally, the diverse aspects of structural control treated in this paper are summarized in Section 5 with the aim of providing guidance to the reader based on the identified key issues.

2. PASSIVE CONTROL SYSTEMS FOR THE SEISMIC PROTECTION OF STRUCTURES

2.1. Seismic isolation and other emerging anti-seismic strategies, in Italy and worldwide

During the audits held in 2012 at the 8th Commission on Environment, Territory, and Public Works of the Italian Chamber of Deputies, in the framework of the «Survey on the State of Seismic Safety in Italy», both Dr. Martelli and the president of the Italian Major Risks Commission emphasized that over 70% of existing Italian buildings is not able to withstand the earthquakes which may hit it [1]. Such a large number of highly seismically vulnerable Italian buildings includes, in addition to many residential buildings, many schools, several hospitals, and numerous other strategic and public structures, often hosted by ancient or just old buildings (or even by relatively recent but poorly constructed buildings), for which seismic retrofit is impossible or too expensive [1]. In such cases, it is imperative to move the functions of schools, hospitals, and other strategic and public constructions to other buildings, which can ensure the necessary safety level or may be adequately seismically retrofitted or ad hoc reconstructed with the best available technologies, by devoting the ancient buildings that cannot be adequately seismically retrofitted to other activities and by demolishing and rebuilding those that are just old. It shall be stressed that, for buildings such as schools (which contain the most valuable asset of each community, that is its future), hospitals, or emergency management centers (which must remain fully operational after any catastrophic event), the complete integrity during an earthquake should be guaranteed. To achieve this goal for existing buildings, the so-called ‘seismic improvement’ may not be sufficient, and it is indispensable that such buildings are put in the same safety conditions as those that are obtainable for the new constructions.

To maximize the seismic protection of structures (for both those of new construction and the existing ones), modern technologies have been developed and have already been significantly applied, even in Italy, for a long time. They are based on both the traditional approach, which aims at making the structures adequately earthquake-resistant by strengthening them, and on an alternative approach, which consists in reducing the seismic actions that the ground transmits to the structure through the use of appropriate devices [2]. As far as this second approach is concerned, passive anti-seismic (AS) systems have been developed, like the SI ones, which are the most effective in terms of protecting the structural integrity and minimizing the ‘panic’ effects, or the ED ones, which allow to come close to such an objective [1,2]. The first Italian building application of SI dates 1981, as a consequence of the 1980 Irpinia earthquake [2,3]. Obviously, the ED systems are less effective than the SI ones, as they cannot totally cancel the deformations of the building (because it is thanks to these deformations that they work) and they do not slow down its movement, so that the ‘panic’ effects cannot be fully canceled.

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The AS systems have already been used to protect more than 23,000 structures (bridges, buildings of all kinds, or industrial plants), both of new construction and existing, in more than 30 countries [4]. In Italy, the correct use of the AS systems has been promoted by the national association GLIS (GLIS—Isolation and Other Anti-Seismic Design Strategies), which is a corporate member of the Anti-Seismic Systems International Society. In this activity, GLIS is also supported by the International Seismic Safety Organization, which was founded in August 2012. The Italian seismically isolated buildings are now over 400.

About schools, the first Italian application of SI concerned the reconstruction of Francesco Jovine primary school in San Giuliano di Puglia (following the collapse of the existing building during the 2002 Molise and Puglia earthquake, which caused the death of a teacher and 27 children) [2,3]. After this application, completed in 2008 and certified as safe by Dr. Martelli, the Italian schools protected by this technique, both of new construction (e.g., the primary school of Marzabotto in Figure 1) and seismically retrofitted, are already at least 30 and others are in progress [5,6].

Isolators are of different types [5,6]: those most commonly used in the world and for which the largest experience has been gathered are the steel-laminate rubber bearings, especially the high damping rubber bearings and the lead rubber bearings. They are often combined to flat surface steel-Teflon sliding devices (SDs), installed in suitable positions, which allow both to support light parts of the building without unnecessarily stiffening the SI system (which would make it less effective), and to minimize the torsion effects due to asymmetries in the structure horizontal plane (the effects of the vertical asymmetries are drastically reduced by the quasi 'rigid body motion' of the isolated superstructure). Another type of isolators, which has been used in Italy after the 2009 Abruzzo earthquake, is the so-called curved surface slider, which derived from the US friction pendulum system (FPS) and the subsequent German seismic isolation pendulum. Finally, there are also rolling isolators (in particular sphere bearings): this isolator kind is very effective and finds numerous applications to protect buildings in Japan, but not in Italy, because there it has been judged too expensive (however, it has already been used, even in Italy, to protect precious masterpieces and costly equipment, including operating rooms in hospitals).

Internationally, there is an ongoing effort to exploit the properties of shape memory alloys (SMAs) in dissipative devices for civil engineering applications. Several examples are mentioned here. Bars in a Cu–A–Be alloy were assembled into an isolator, which was studied experimentally in the laboratory, simulated numerically, and introduced in a bridge benchmark [7]. In view of matching the benchmark requirements, the analytical model of the SMA device was incorporated in the control force equation of the sample passive device. The effects of the proposed passive device on the dynamic response of the benchmark highway bridge were studied for different ground motion excitations. The results showed that the SMA isolator can aggressively limit peak bearing and displacement response quantities during strong earthquakes. However, this is achieved at the cost of an increase in peak base shear and overturning moment. In a different study, small diameter bars were conveniently used for the mitigation of vibrations in portico-like systems [8] and it was outlined that rather than a general purpose numerical material model, one should adopt case-specific numerical models in the structural analyses. These models need to account for the temporal scale, the spatial scale, and the thermo-mechanical treatments of preparation of the alloy, and they should provide consistency with the results of a suitable experimental campaign. In a third and ongoing study, Ni-Ti wires are being studied for applications in

Figure 1. Left: the new seismically isolated primary school in Marzabotto (Bologna), former Italian seismic zone 3, which was opened to activity in September 2010, with safety certification of Dr. Martelli. At the center and right: two of the 28 high damping rubber bearings and one of the 14 sliding devices that form the seismic isolation system of the school.

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mitigating cable vibrations [9]. The investigation is still in progress with attention being focused on the fatigue properties offered by elements in Ni-Ti alloys adequately prepared toward specific performances. It is noted that shape memory alloy devices have also been used in Italy, some years ago, as 'force limiters' in the retrofit of some important monumental buildings (that of the Upper Basilica of St. Francis in Assisi, which had been severely damaged by the 1997–1998 Marche and Umbria earthquake, was the first application of this kind at worldwide level [2,3]).

A new seismic isolation bearing, called roll-n-cage isolator, has been proposed in the last few years by the research group at UPC, Spain [10]. It integrates several passive mechanisms into a single unit and is mainly based on a rigid body with a carefully designed geometry rolling in permanent contact with two horizontal plates. The lower plate is fixed to the ground, while the upper plate is the one attached to the isolated structure. The system incorporates damping, buffers, and self-centering capacities. Experiments have been conducted to characterize some physical prototypes, and numerical studies have assessed the effectiveness to isolate buildings [11] and bridges [12].

The improved performance in terms of acceleration response to design seismic actions of isolated buildings with respect to traditional ones makes isolation techniques a very attractive choice also for reactor buildings in future nuclear power plants. In light of this consideration, the probabilistic evaluation of the seismic fragility of the reactor buildings of a nuclear power plant including passive seismic isolation was the object of recent research activities carried out at Politecnico di Milano [13], at ENEA [14], and at other partners' facilities.

Seismic isolation, however, is a technology of great interest not only for public or strategic buildings, but also for the residential ones [2,3,5]. Indeed, in addition to confer a level of seismic safety much higher than that obtainable with conventional foundations and to allow to avoid the costs (of repair, demolition, reconstruction, relocation, etc.) that, after a significant earthquake, should be faced for the structures with conventional foundations, the use of SI entails, for new buildings, a very limited additional construction cost in Italy. This cost decreases with increasing seismic hazard of the area where the building is located, number of its floors, and extent of its structural asymmetries [3].

Finally, for interventions on the existing buildings, the use of SI could even cause a saving [2,3]: in fact, it is not necessary to 'undress' the structure, so as to be able to stiffen beams and nodes, or to insert shear walls (which is often quite complicated). In addition, if the intervention is carried out as a preventive measure (that is, before the building is damaged by an earthquake), it is often possible to keep the building in use (except, of course, for the story at which the isolators have to be inserted and, to this end, pillars and/or load-bearing walls have to be cut and, if necessary, strengthened); this advantage is of particular importance for the retrofit of hospitals.

The at least limited additional construction costs of SI in Italy are due to the seismic code currently in force in this country, which allows to partially take into account, in the design, the drastic reduction of seismic forces that is caused by SI. Obviously, however, this implies the need both to pay great attention to the selection, design, qualification, acceptance, and installation of the isolators and to ensure that the SI devices and the so-called 'interface elements' (e.g., stairs, lifts, gas pipes, and all other safety-related pipes that cross the isolation interface) remain in the same operating and safety conditions that were foreseen in the design, during the entire useful life of the structure. These tasks can only be achieved through periodic inspections of the SI system, the structural gaps, their protections, and the 'interface elements', as well as, where necessary, through maintenance and replacement of the isolators, their protections, and joints of the 'interface pipes'. Otherwise, the isolated building would be less safe than a conventionally founded one, having been designed by assuming lower seismic loads.

Seismic isolation is, therefore, the technology that, nowadays, should be used, in a seismic zone, both for the construction of all new buildings, at least of the public and strategic ones (first of all for the new schools and new hospitals), and for seismically retrofitting the existing ones. In the latter case, however, this technique is usable only if structural gaps of sufficient width as to allow the free transverse displacement of the isolated superstructure are present or are realizable: this displacement can reach 40–50 cm in Italy (1 m or more in more highly seismic areas, such as Japan and California). When such gaps are not present or feasible, it is necessary to adopt other technologies, such as ED.

2.2. Viscous dampers for energy dissipation

2.2.1. Case studies in Turkey. Recently, there has been both analytical and theoretical research in Turkey regarding the application of viscous dampers in structures [15–20]. These analytical studies refer to the effects of viscous dampers on structures under earthquake excitation and the optimal placement of viscous dampers within a structure.

Aydin *et al*. [15] investigated optimal damper distribution for seismic rehabilitation of planar building structures. They chose the transfer function amplitude of the base shear force evaluated at the undamped fundamental natural frequency of the structure as an objective function, instead of the usual choice of transfer function amplitude of top displacement of the structure. It is shown that the proposed procedure based on the transfer function of the base shear force is beneficial in the rehabilitation of the seismic response of the structures. Guneyisi and Altay [16] performed seismic fragility studies to assess the effectiveness of viscous dampers in R/C buildings under scenario earthquakes. The fragility curves in this study were developed as a function of peak ground acceleration, spectral acceleration and spectral displacement. They indicated that the fluid viscous dampers were very effective in attenuating seismic structural response under various earthquake ground motions. Aydin *et al*. [17] examined variations on seismic response via viscous damper placement in a five-story planar building structure. They constructed and analyzed a five-story main structural model planar building, and 15 damper distributed sub-models to understand the best suitable damper design in terms of some structural response parameters such as story displacements, inter-story drifts, and story accelerations. The results of analyses showed that proper dampers distribution relatively changes in terms of different response parameters.

Aydin *et al*. [18] studied the application of viscous dampers for prevention of pounding effect in adjacent buildings. They examined the effect of optimal damper design on pounding prevention of the buildings by means of relative displacement response spectrum. Aydin [19] investigated optimal damper placement based on base moment in steel building frames. He developed a new damper optimization method for finding optimal size and location of the added viscous dampers based on the elastic base moment in planar steel building frames. The results showed that the proposed method is beneficial to decrease both the base moment and the inter-story drift ratios in some frequency regions. Sonmez *et al*. [20] used an artificial bee colony algorithm (ABCA) for the optimal placement of viscous dampers in planar building frames. They proposed an optimization algorithm based on the ABCA. The numerical results showed that the use of the ABCA can be a practical and powerful tool to determine the optimal damper allocation in planar building structures.

In Turkey, viscous dampers were applied at Ataturk Airport (Istanbul) and at its Expansion. In 2000, a total of 120 fluid dampers, each one of which had a stroke of 45 kN ± 25 mm, were installed at Ataturk Airport. They were used at the new international terminal with FPS isolators to control deflection and minimize thermal restrictions. Afterwards, a total of 68 fluid dampers, each one of which had a stroke of 45 kN ± 25 mm, were deployed at Ataturk Airport Expansion in 2002. These additional damping devices were required to control deflection and minimize thermal restrictions of a roof structure supported on FPS isolators. These dampers, which were utilized for seismic protection of the Ataturk Airport, consisted of two major parts which were a cylinder and a piston rod. It was constructed in a through-rod configuration which is shown in Figure 2. A thin cylinder containing small orifices was attached to the piston rod inside the larger, hollow cylinder that makes up the main body of the damper. The silicone fluid was forced to pass through the orifices at a high speed as the damper was stroked [21].

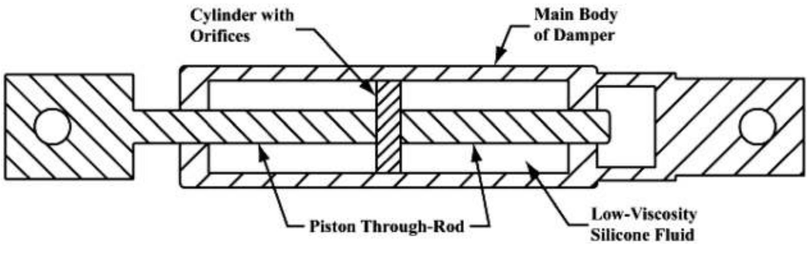

Figure 2. Fluid viscous damper with through-rod configuration [21].

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Currently, application of viscous dampers is not common in Turkey, because they are not manufactured locally and are imported from overseas. This situation causes viscous dampers to be very expensive and not to be preferred compared to conventional construction approaches. However, there is a need for high-rise buildings in metropolitan cities like Istanbul. It is presumed that there will be a significant need for the use of viscous dampers in the Marmara Region, which is located in a very dangerous earthquake zone. It is known that the use of viscous dampers will help the dimensions of structural elements to be reduced and will reduce the construction cost of structures, excluding the cost of viscous dampers themselves. In addition, there is need for a viscous damper application part in the Turkish design code for buildings.

2.2.2. Prestressed damping device and shaking table tests at IZIIS. A viscous prestressed damping device (PDD), compounded of a spring and piston in a closed container filled with a special mixture of a silicone gel developed by GERB Schwingungsisolierungen GmbH & Co. KG from Germany was the object of recent studies [22–25] carried out at IZIIS, in the Republic of Macedonia. A research program has been proposed in order to estimate the efficiency of the PDD in controlling the structural response due to seismic excitations and further to develop a procedure for optimal design and placement of these and similar devices in the process of earthquake-resistant design of structures.

Realization of the research program was divided in three phases:

1. Experimental—shake table testing.
2. Analytical modeling and efficiency estimation.
3. Developing of a procedure and algorithm for the optimal design and placement of PDDs.

In the first phase of the research related to experimental investigation, an appropriate testing procedure has been conceived and fully realized [22,23]. Namely, a hypothetical steel frame structure has been designed in accordance with the latest Eurocode 3 and 8 requirements and tested on the 5 m × 5 m MTS 5 DOF shake table at IZIIS' Dynamic Testing Laboratory, without and with PDDs under simulation of seventeen different real recorded earthquake time histories. Five different configuration of the same structural model, one without (Model01) and four (Model02–Model05) with PDDs having different position along the height of the frame structure have been tested. The total mass of the tested structure is approximately 25.0 t, including added mass of steel ingots on each floor supported by secondary longitudinal beams in such a way that they have no influence in changing of the stiffness of the structure. In Figure 3, Model05 is shown as it has been tested on the IZIIS' shake table.

By shake table testing of the model structure with and without PDDs, it has been demonstrated that this system is capable to substantially reduce the responses depending on the frequency content of the seismic input and the corresponding sensitivity of the structure [24]. Recorded response histories, more than 19400, were a very good basis for developing of appropriate analytical models for the tested structure without and with PDDs [25]. The developed analytical model of PDDs is currently being used in the other two phases of the research program, i.e., the analytical estimation of the efficiency of the PDDs on various steel frame structures exposed to different seismic excitations, for improvement of

Figure 3. Model05.

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the PDDs characteristics, as well as, the development of a practical procedure for optimal design and location of these and similar devices in the process of earthquake-resistant design of structures.

2.2.3. Visco-elastic coupling of adjacent structures: L'Aquila case study. Modern engineering systems are often conceived as complex structural schemes composed of two or more collaborating substructures which, due to functional specialization, may possess strongly different physical properties. As a consequence, in the presence of weak stiffness coupling, two sub structures may develop a quasi-independent linear dynamics, typically revealed by the co-existence of a pair of local modes, or a local and a global mode with well-distinct frequencies. For particular parameter combinations, these modes may also give rise to potentially dangerous internal resonance conditions [26]. Therefore, the feasibility of dissipative connections could increasingly be evaluated not only to reduce the pounding risk and mitigate the dynamic response in adjacent buildings, but also to limit the energy transfer among different substructures and, especially, avoid the vibration localization in the substructure with higher vulnerability (i.e., more flexible or less structurally damped).

Several different criteria have been proposed to assess the design parameters of dissipative connections between adjacent structures, not always leading to closed-form formulas, as would be desirable for easy practical implementations. It could be noted that several criteria for the passive control design of tuned mass dampers could be extended to adjacent structures [27], with some care in considering that none of the two oscillators in the synthetic model can be regarded as a merely sacrificial appendix, as sometimes happens for the tuned mass. From a different viewpoint, promising design-oriented perspectives [28,29] have been recently opened by the parametric investigation of the solution (damped frequencies and modal damping ratios) of the non-classic modal problem associated to the visco-elastically coupled oscillators [30].

The resonance-based criterion [28,29] has been employed in the preliminary design phase of the seismic retrofitting intervention, which has recently interested the Engineering Faculty of the

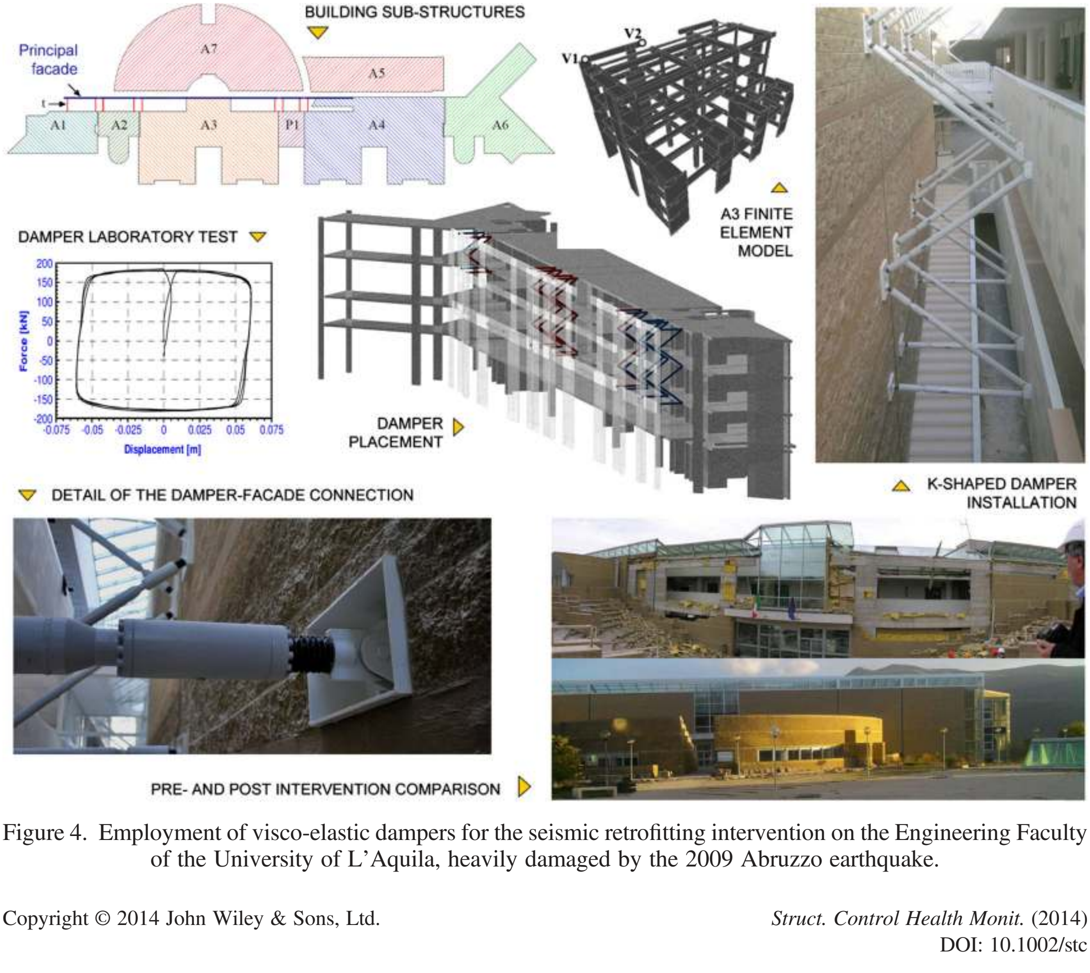

Figure 4. Employment of visco-elastic dampers for the seismic retrofitting intervention on the Engineering Faculty of the University of L'Aquila, heavily damaged by the 2009 Abruzzo earthquake.

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University of L'Aquila (Figure 4), heavily damaged by the devastating earthquake (mainshock magnitude $M_w = 6.3$, hypocenter depth $d_h = 9\,km$) which struck the mountainous upcountry of the Abruzzo region in April 2009 [31]. The Engineering Faculty sits on a hilltop, about 2 km far from the epicenter. The Building A of the Faculty, built in the mid 90s of the past century, is a four-story building, with two partially underground levels, and features a complex geometry marked by strong horizontal and vertical irregularities. The reinforced concrete resistant structure is composed of seven independent substructures (A1–A7), separated by seismic joints (Figure 4, top left). All the substructures can be classified as a mixed moment-frame and shear-wall typology, with significant stiffness eccentricities.

The seismic events caused severe damages, prevalently of non-structural type, including diffuse collapse of light and heavy infills, which completely compromised the building functionality. The most important structural damages interested the steel rods connecting the stiff substructures A1, A2, A3, and A4 with the free-standing principal façade, a sort of curtain wall made of heavy split-face brick masonry and large glass portions, supported by a self-sustaining planar frame with high out-of-plane flexibility. These rods turned out to be under-dimensioned and thus inadequate to limit the out-of-plane displacements and acceleration of the principal façade, according to both early post-earthquake surveys and numerical simulations [32]. Finite element analyses, in particular, have clearly evidenced a quasi-independent dynamics between these weakly connected substructures. This evidence prompted to replace the inadequate system of connections with a diffuse network of visco-elastic dampers (Figure 4), engaged by the relative motion of the two substructures, treated as almost independent adjacent structures, with the principal aim to passively control the vibration amplitudes of the planar frame supporting the principal façade, more vulnerable.

After the preliminary design stage, the intervention design has been developed through a multi-faceted multi-phase process [33], including (i) experimental modal analyses to identify the structural parameters; (ii) model updating to calibrate finite element models according to the experimental measures; (iii) optimization of the size, number, and placement of the visco-elastic dampers, by comparing and iteratively refining different options according to simultaneous criteria of structural efficiency, economic costs, and esthetic outcomes; and (iv) structural analyses to verify internal forces, displacements, and accelerations with respect to different strength and serviceability limit states. The final solution for the passive control system counts on dissipative steel bars, embedding visco-elastic dampers (of two different sizes) and arranged in a stiff K-shaped configuration, reproducing a planar truss structure of connections. The structural analyses have been based on a number of nonlinear numerical simulations for the evaluation of the structural response to several acceleration time histories, with spectrum characteristics compatible with the near-fault site. The nonlinearities characterizing the viscous behavior of the selected damper, experimentally identified, have been accounted for in this analysis phase. The retrofitting intervention, including also several minor structural improvements, has been successfully concluded at the end of 2011.

3. SEMI-ACTIVE, ACTIVE, AND HYBRID VIBRATIONS CONTROL STRATEGIES

3.1. Semi-active dampers and their applications in Europe

Semi-active devices can be regarded as passive ones able to adjust their reaction online with the external excitation through suitable algorithms. Managing their intrinsic dissipation level or stiffness, removing energy from the system or decoupling the structural motion from the base external excitation, they have been shown to significantly outperform the passive schemes by a moderate energy supply. Their practical installation in a wide variety of structures demonstrates their positive function on alleviation of wind and seismic response of buildings, sometimes showing better performances than active systems, which usually are considered the best performers in terms of internal forces and displacements reduction. Acting simultaneously with the hazardous excitation, they also provide enhanced structural behavior for improved usefulness and safety, making the semi-active techniques a very attractive choice for buildings whose functionality is of paramount relevance.

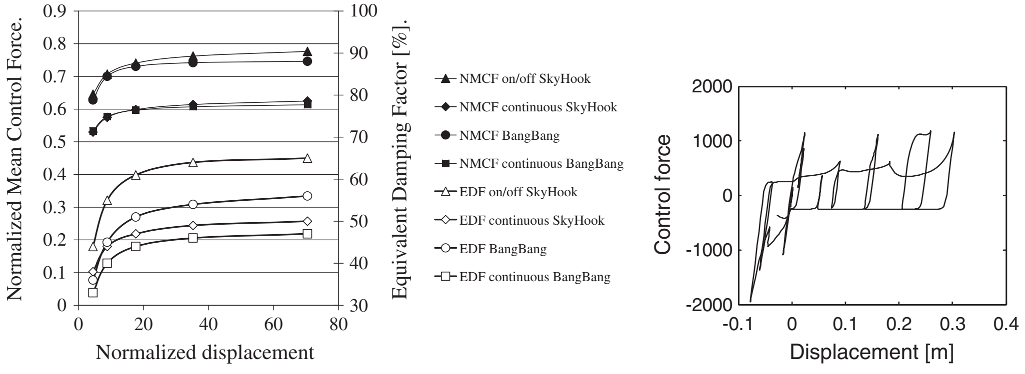
The numerical simulation of control devices allows evaluating their efficiency into complicated structural systems, as high-rise buildings or long span bridges, under a wide variety of external forces. The solutions adopted for simulating conventional semi-active dampers, such as the electro-inductive (EI) and Magneto-Electro-Rheological (MR-ER) ones, reveal able to reproduce the inherent characteristics of the physical systems, consequently improving their knowledge.

The Bouc–Wen (BW) model in its original formulation [34] has proven to perform with reasonable efficiency in reproducing the force's hysteretic component of real passive devices, playing a major role among other differential ones. It can reproduce also the hysteresis signature coming from a wide range of semi-active damper technologies, e.g., an innovative EI one characterized in laboratory for structural control applications on bridges [35]. It represents a fascinating solution for the feasibility of larger passive devices of this type to be installed in long span bridges. This is of interest due to two facts: they are much shorter than passive hydraulic dampers of identical maximum stroke, and they can easily be converted into the semi-active type, adapting themselves to different seismic intensity levels by using specific control laws. An additional aspect to be underlined of such devices is the self-centering ability after an extreme loading event, realigning the deck with its original axis and the towers.

In this light, an operational method for modifying in real time the hysteresis cycles has been developed, through suitable semi-active laws embedded into the BW numerical model, with promising consequences of practical interest [36]. When semi-active systems are employed in real applications, the information collected from the monitoring system is processed by suitable algorithms. Subsequently, the damper configuration is modified so as to exert the necessary control reactions. The same procedure can be translated into the simulation environment, where the BW model parameters are updated to modify, as needed, the hysteresis forces which represent the control actions during the real-time mock-up. The proposed methodology for embedding semi-active algorithms and achieving the semi-active BW expression, considers three different control laws, suitable for managing dissipative devices: the on/off *SkyHook*, the continuous *SkyHook*, and the *BangBang* [37]. An innovative one, called *continuous BangBang*, is also introduced [36]. The proposed procedure has been demonstrated effective for managing, in real time, the hysteresis component of semi-active systems defining the proposed semi-active version of the BW model.

Figure 5a depicts the mean control force and equivalent damping factor for semi-active dampers with identical sinusoidal input time histories, at increasing amplitudes, for reproducing a standard motion of the dampers connection points. Forces and displacements are here normalized to the device highest yielding level. Four different control algorithms are implemented; namely, the *SkyHook*, the continuous *SkyHook*, the *BangBang*, and the continuous *BangBang* law. A significant decoupling of relative motions between the support and body mass to be controlled, with respect to the discrete algorithms, is exerted by the continuous semi-active laws; on the contrary, highest dissipation levels are provided from the discrete ones. Exploring the seismic response, Figure 5b reports the characteristic of the semi-active BW model (*continuous BangBang* algorithm) employing the Kobe record as input.

Several results from literature [36] are intended as a realistic validation of such innovative semi-active technology implementation on bridges by numerical simulations through finite element models. Furthermore, several aspects of interest as optimal control design against wind buffeting



(a) (b)

Figure 5. (a) Restrain and dissipation versus different input cycle amplitudes. (b). *Continuous BangBang* hysteresis with Kobe record.

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and seismic excitations, control system decentralization, and mitigation of direct structural effects (e.g., displacements and accelerations) have been investigated [38,39]. Protection of composite decks in long span bridges against fatigue damage through decentralized control schemes is currently under investigation by the research group at Politecnico di Milano, as well as the issue of robustness when determining the devices distribution on large structures.

Focusing on MR dampers, a relevant effort has been devoted in the last few years by the research group at UPC, Spain, toward the implementation of semi-active control strategies. Indeed, because the MR dampers are non-linear devices that cannot apply purely active forces, their mathematical characterization represents a major issue in the control formulation. A normalization of the Bouc–Wen model [40,41] has been the base for developing inverse models of MR dampers for control purposes [42–44].

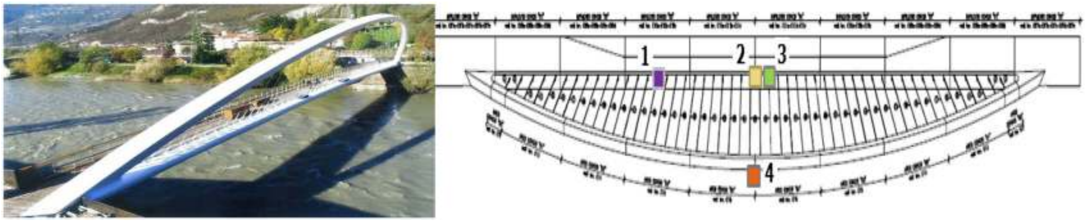
Furthermore, the semi-active control strategies presented in the literature are developed to manage a single MR damper or, in the case of multiple MR dampers, they receive, in general, the same command voltage. In [45], a new practical method has been defined based on a hierarchical strategy that allows a decentralized control of a set of MR dampers in base-isolated structures. A semi-active control law is proposed in [46] based on the idea of clipping the voltage signal but using a simpler proportional and integral (PI) control. The PI parameters are computed so that the closed-loop is stable, its response is minimized and robustness against modeling errors is guaranteed.

The effectiveness of force-derivative feedback semi-active control scheme for vibration reduction of base-isolated building structures employing an experimentally identified large-scale MR fluid damper is investigated in [47]. In this work, the MR damper is scaled up to represent a real-manufacturable MR damper device.

Moving toward real applications, the Nomi footbridge is currently under study by the research group at University of Trento, Italy. It is a single span, pedestrian arch bridge (Figure 6a), crossing the river Adige, and located between two northern Italian towns Nomi and Calliano. The footbridge is entirely made of Corten steel and has length and width of about 102 and 5 m, respectively. The arch is oriented in the transverse direction along a 30° inclined plane and is endowed with a rectangular varying cross section. In order to control pedestrian induced vibrations [48], three passive tuned mass dampers (TMDs) and one semi-active MR-TMD were installed on different positions of the footbridge as illustrated in Figure 6b, on the basis of relevant finite element dynamic analysis.

In order to deal with unreliable measurements (due to uncertainty of soil stiffness and temperature variations) of the modal frequency to be damped, a passive TMD for vertical vibrations at 1.43 Hz was replaced by a semi-active MR-TMD, which was characterized by means of experimental tests. The experiments were conducted in a versatile test rig named TT1, which is equipped with Parker electric actuators, accelerometers, displacement, and force transducers and is capable of being controlled through a Matlab/Simulink platform via dSPACE. A test set-up for the MR damper identification and the relevant experimental force–velocity curves are presented in Figure 7a and b, respectively.

With regard to the control strategy, in a first phase, the behavior of the MR damper was numerically simulated by means of the classical Bouc–Wen model [34]. The semi-active control was implemented through a clipped optimal control strategy [49,50] that calculates the command voltage at each step and incorporates two parts. The first part consists of the design of an active control law for an ideal active damper; every type of control law can be applied. In the second part, the clipping controller develops a force matching the desired control force.



(a)　(b)

Figure 6. (a) The Nomi footbridge; (b) positioning of dampers (2: MR damper).

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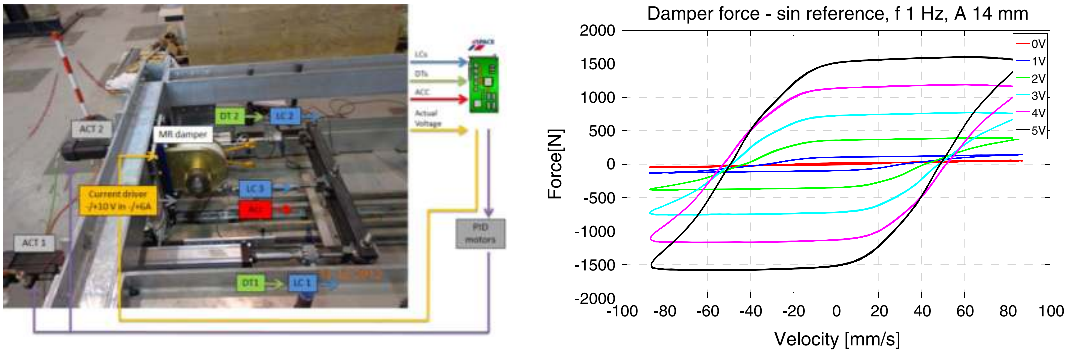

(a) (b)

Figure 7. (a) Control and acquisition instrumentations set-up in the TT1 test rig; (b) experimental force–velocity curves of the MR damper for 1 Hz sinusoidal excitation with amplitude of 14 mm, for different level of applied voltage.

The MR-TMD active control was based on the theory of optimal control and more precisely the damper was controlled by a linear quadratic Gaussian control [51]. The components of the semi-active controller are shown in Figure 8. In an MR damper, a voltage v is applied to the current driver which supplies current to the damper that modifies the MR properties to generate the desired control force. In order to reproduce the ideal damping force, the semi-active logic reads the force f_{MR} yielded by the damper and its sign; if f_{MR} is less than the ideal control force f_c and if $signum(f_c - f_{MR}) = signum(f_{MR})$, the voltage applied is at the maximum level V_{MAX}; if not, the applied voltage is zero.

3.2. Active and hybrid vibrations control: related algorithms and implementation aspects

Large structures, as tall buildings and long bridges, can be considered as complex systems decomposed into interconnected subsystems. Under this framework, a set of decentralized controllers may be independently designed. Some of the advantages of this scheme are the following: (1) lower computational cost; (2) minimal information exchange; and (3) reduction of the effect of disturbances and failures. The work in [52] presents a new method in designing static output-feedback controllers for control of buildings under seismic excitation. The method produces a linear matrix inequality formulation that allows obtaining a gain matrix with different information structure constraints by imposing a convenient zero–nonzero structure on the linear matrix inequality variables. The application of the proposed methodology is illustrated by designing centralized and decentralized velocity feedback H_∞ controllers.

An application of decentralized control schemes can be found in [53]. They present a structural vibration control strategy for seismic protection of adjacent structures that combines interstructure passive damping elements with local feedback control systems implemented in the substructures.

Structures are systems that include components and devices with a non-linear nature, which suggest the formulation of non-linear control algorithms. The backstepping control design is based on the

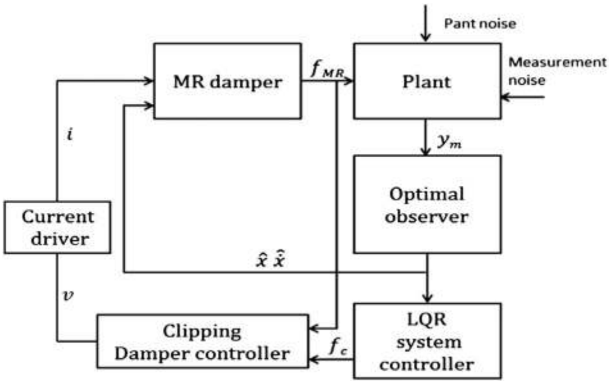

Figure 8. Linear Quadratic Gaussian (LQG) clipped control scheme.

recursive computation of pseudo control inputs for lower dimension subsystems of the overall system. The final result is a feedback design with guaranteed stability based on Lyapunov functions. A digital formulation of this non-linear technique can be found in [54], where a base-isolated structure is used for numerical performance assessment.

A velocity-based active vibration control, along with a special class of hysteretic models using passive functions, is presented in [55]. This hysteretic model is based on a modification of the Bouc–Wen model that retains the rate-independence property, and it is able to reproduce several kinds of hysteretic loops that cannot be reproduced with the original Bouc–Wen model. The control scheme is able to mitigate seismic perturbations on hysteretic base-isolated structures.

The work by Pujol *et al.* [56] presents a control scheme based on using a passive static hyperbolic function depending only on velocity measurements. This function ensures ED capability with always-bounded control force. A practical feature is the simplicity in formulation, design, and implementation. This expression can be seen as an active control law, which can be implemented by an appropriate actuator using only local velocity feedback. Exploring the possibility of implementing this control scheme by means of an MR damper, it was proved in [57] that a smooth command voltage function was able to produce in the MR damper a force–velocity relationship as in the hyperbolic control. This control scheme was applied in both a benchmark highway bridge [56] and a base-isolated benchmark structure [57].

A hybrid control policy that combines a distributed passive solution with an open-loop actuation is proposed by Faravelli *et al.* [58] for cable vibration mitigation. Preliminary results are obtained by using simplified numerical models and verified experimentally by carrying out laboratory tests on a physical cable model.

Model order reduction techniques are traditionally adopted to build models tractable by dynamic analysis in practical control design. The goal is to reduce the computational effort and maintain the ability to estimate the input–output mapping of the original system in an important region of the input space. In [59], the consequences on the achieved accuracy of adopting different reduction technique patterns are discussed mainly with reference to a linear case study.

The practical implementation of active control strategies requires a properly integrated design of all three components: the monitoring system, the control law, and the actuation. A first laboratory facility was realized at the University of Pavia, Italy, in 1994. Sensors, controllers, and actuators were all wired with no minor operational difficulties. In the last years, a medium term research program was formulated and developed [60] in order to introduce wireless links and a digital controller into a structural control system for a reduced-scale three-story steel frame mounted on a shaking table. The structural control system mainly consists of four accelerometers, a controller, and an active mass damper as actuator. The designed wireless sensors are based on the use of recent low-power System-on-Chip wireless CC1110 transceivers, which integrate an 8051 microcontroller core and are able to operate in most of the license-free ISM (Industrial, Scientific, and Medical) frequency bands. The requirement of multi-channels, continuous and real-time data transmission of the feedback signals is supported by a frequency division multiplexing technology, based on which a dedicated frequency band is assigned to each sensor unit. In this manner, the data transmission can occur simultaneously without conflicts. The power management unit [61] for the wireless sensor stations is designed to be adaptable to the voltage and power consumption requirements of different kind of sensors, making the system suitable to a readily available replacement of existing analog connections. The active mass damper is driven by a newly designed digital PID (proportional, integral, and derivative) direct current motor controller, which is based on the high integration power amplifier LMD18200 and the enhanced 8051 core in CC1110. Validation of the system is experimentally achieved by maintaining the same performance of the original wired control system.

3.3. Vibration control strategies for wind turbines

Vibration control of wind turbines is a new and developing area of research mainly with the increased size and flexibility of rotor blades, and tower interactions. The primary aim in the design of a wind turbine is to maximize the power output under specified environmental conditions and hence this has led to the development of larger turbines with increased rotor diameters. Uncontrolled vibrations may not only induce fatigue in mechanical components and blades, but also lead to significant

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reduction in power production, operational efficiency, reliability of connection to power grid due to increased downtime, and lifetime of wind turbines. The main modes of vibration in turbine blades are in-plane (predominantly edgewise) and out-of-plane (predominantly flapwise), which are coupled together because of the presence of structural pre-twist. Between the two modes, the edgewise vibrations are lightly or negatively damped aerodynamically and can lead to violent vibrations leading to instability while the flapwise mode is a major contributor to fatigue. Recognizing the importance of controlling vibrations in wind turbines, active and semi-active control strategies have been proposed recently.

The application of active devices has been considered by researchers to suppress rotor vibrations. The hollow nature of wind turbine blades makes them suitable for the installation of control devices to mitigate the dynamic response without affecting the aerodynamic performances of the structure. For example, for ease of installation inside the blades, the use of active tendons is proposed for the control of edgewise vibrations by Staino *et al*. [62]. Similar active control strategies have been used by Staino and Basu [63] for controlling vibrations in turbines with variation in blade rotational speed. The active tendon methodology consists of providing cable anchorage to the structure by using an actuator which controls the axial force in the cable or the displacement of the cable support. The proposed vibration control scheme is shown in Figure 9. The active elements are drawn in thin lines while the support structure (e.g., a truss or a frame) is shown in bold. An appropriate control strategy can be applied to synthesize the control force to be applied to the blade to suppress undesired vibrations. For the *j*-th blade in a wind turbine, the net force from the actuators/tendons is proportional to the force $T_j(t)$ and the sine of the angle ϕ_0. In another study, active tuned mass dampers for control of in-plane vibrations of wind turbine blades have been proposed by Fitzgerald *et al*. [64]. A wind turbine was modeled as a time varying multi degrees of freedom system under turbulent aerodynamic loading with the active tuned mass dampers installed inside the blades (Figure 10).

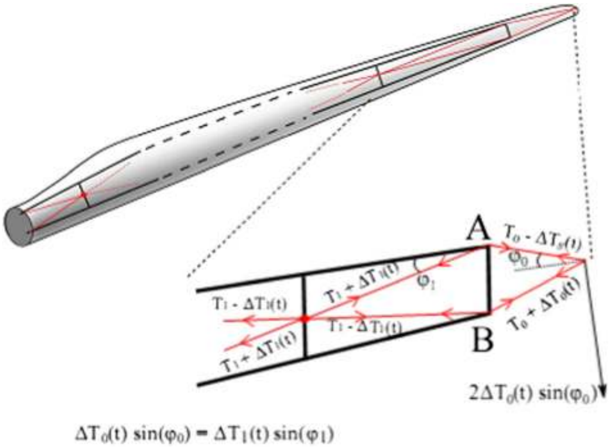

Figure 9. Implementation of vibration control based on active tendons.

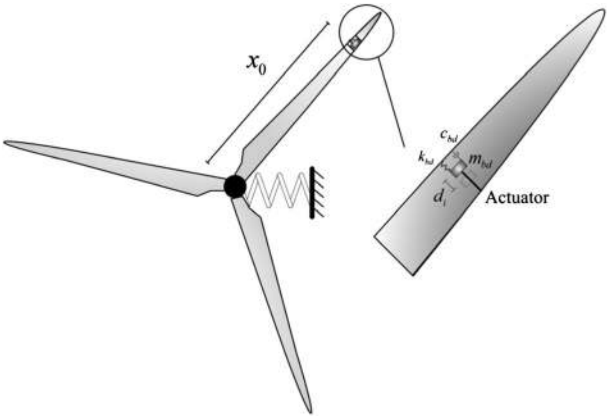

Figure 10. Active tuned mass dampers inside blade.

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A semi-active method based on tuned mass damper has been proposed by Arrigan *et al.* [65,66] for controlling the flapwise and edgewise vibrations of wind turbine blades. The aim of the proposed algorithm is to adaptively tune the semi-active tuned mass damper to cater for changes in the structural and/or operational conditions (such as rotational speed) of the wind turbine. A frequency tracking algorithm based on the short-time Fourier transform technique is used to tune the damper. The short-time Fourier transform algorithm developed allows the semi-active tuned mass damper to be tuned in real-time to the dominant frequencies in the system. The semi-active algorithm is illustrated in Figure 11.

Electrical grid faults can be a source of significant structural vibrations in wind turbines, generated due to the mismatch between mechanical and electrical torques. Tower oscillations have been observed due to voltage sag arising out of electrical faults. Similar vibrations can affect wind turbine blades. Basu *et al.* [67] have used electrical custom power devices and flexible alternating current transmission system devices to mitigate grid fault-induced vibration in wind turbine systems interconnected to grid network.

4. DEVELOPMENT OF ADAPTATION STRATEGIES

4.1. Finite state control strategy for adaptive structural envelopes

The finite state control strategy (FSCS) is a general procedure that has been developed for the realization of adaptive structural envelopes. When the concept of adaptivity is related to the field of civil structures, specific issues, such as the scale factor and the time, have to be considered. Dimensions, mass, and the presence of people are typically going to constrain the possible range of accelerations and velocities during adaptation, not to mention displacements and trajectories of the moving elements. As a consequence, the adaptive behavior cannot belong to nor can come from all the elements of the structure at the same time. Specifically, referring to buildings, the existing proposals involving structural adaptivity are in fact usually focusing on the internal and/or external envelope—i.e., the 'building skin'. Restricting adaptivity to the building skin means that mechanisms are developed exclusively at the boundary, thus reducing kinetic inconsistencies with the internal space and possibly allowing a main static structure to be the core of the building. This, in turn, implies that adaptivity tends to come from mechanisms distributed all over the envelope in order to provide a better change of shape, and a consequent distribution of the actuators is also expected.

The procedure is basically a combination of two main parts: a meta-heuristic optimization process, which aims at discovering new optimal configurations—i.e., finite states—according to some defined purpose, and a gradient-based optimization process, which acts as a constraint for the kinematic

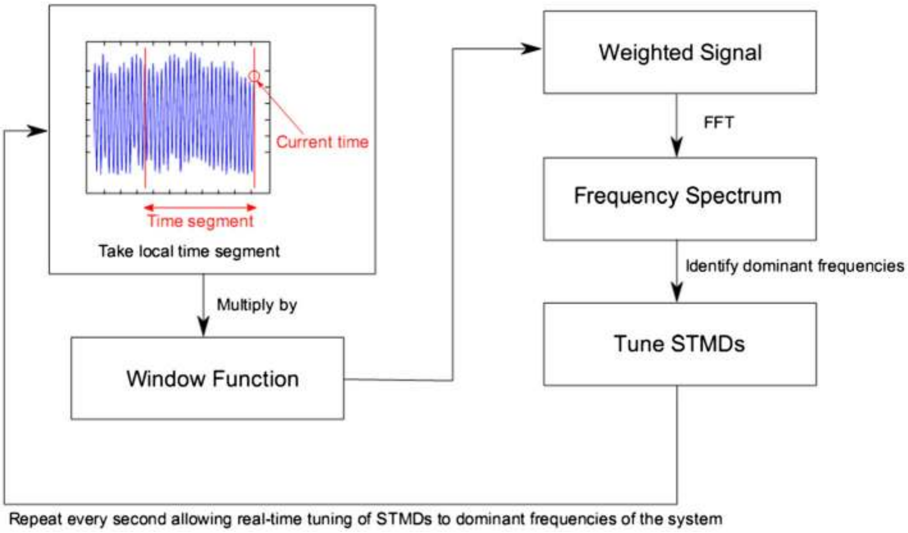

Figure 11. Semi-active vibration control algorithm.

compatibility maintenance. Finally, a topology optimization process, which aims at decreasing the number of degrees of freedom of the structure while retaining its ability to achieve the optimal configurations, is proposed as an integration of the finite states selection.

The main advantage of the FSCS is that a set of optimal configurations (i.e., finite states) are investigated during the design phase. The proposed strategy can handle any kind of system, which can be associated to a framework representation [68]. The framework representation is central to the strategy development, mainly because the matrix analysis of frameworks is used to control the kinematic properties of the envelope. Rigid foldable origami, tensegrity, and many other variable geometry structures belong to this class of systems.

The key steps of the constrained optimization process are the optimization of the different configurations of the envelope (finite states selection), the post-optimization of the framework topology and the management of the actuators location. A detailed description of the two main blocks of the FSCS (performance optimization block and topology optimization block) is reported in [68,69]. The initial framework has to be equivalent to a triangular mesh. The choice of this initial mesh is determinant to achieve a good result. The topology of the initial mesh—i.e., how the edges are connected—is another important factor because it constrains the ‘folding’ process. It is for instance important to start with a symmetric pattern if the mesh is expected to fold symmetrically. Topology and density of the initial mesh could then be part of the whole optimization process but, on the other hand, these two elements are also fundamental to the definition of the envelope appearance. Consequently, they are considered as architectonical parameters fixed by the designer’s choice and left outside the optimization process.

The FSCS procedure has been applied [70] to the conceptual design of an adaptive ceiling for a concert hall, for ensuring an uniform distribution of the sound energy with different configurations of the floor area (Figure 12a), and of an adaptive façade of a tall building, to potentially control the vortex shedding phenomenon (Figure 12b). In both cases, a rigid foldable origami scheme has been adopted for the adaptive skins.

4.2. *Adaptive impact absorption*

Structural adaptivity is the crucial issue to formulate new, challenging technological objectives. Having structure equipped with sensors monitoring its loading conditions and with actively controlled devices able to modify its local stiffness or damping characteristics, the capacity for absorption of unexpected extreme loads can be significantly enlarged. In particular, the so-called Adaptive Impact Absorption (AIA) systems can lead to dramatically better structural responses to critical overloading and to important improvement of its safety. First developed for safety reasons in transport engineering, the AIA techniques are applicable to protect civil infrastructure as well. Challenging requirements for an AIA system generate the following main research problems to be solved:

- online impact load identification (initial velocity and impact energy),
- optimal design of fender systems equipped with so-called structural fuses and active control of these optimally located, adaptive shock absorbers,
- development of new concepts for highly efficient, impact absorbing systems, and
- investigation of limitations for AIA system performance.

The effective mitigation of dynamic structural response to impact loads is the main motivation of the undertaken initiative.

The following example demonstrates the potential of the AIA concept [71]. Computer simulations of the contact forces for the pneumatic fender protecting the off-shore installation of a wind turbine equipped with the AIA system against ship collision are shown in Figures 13 and 14. The initial pressure is tuned to the identified online impact scenario and is released step by step by the controlled valve during the impact process. Figure 13 demonstrates the AIA system ready for impact absorption (a) and in the state just after collision (b). In Figure 14, the system response is represented in the cases of: (a) a fully locked valve and a valve optimally, but constantly opened, and (b) an actively controlled online valve. The optimal, constant valve opening leads to pressure reduction in the fender and reduction of deceleration level by 50% (Figure 14a). The improved strategy assumes an additional increase of

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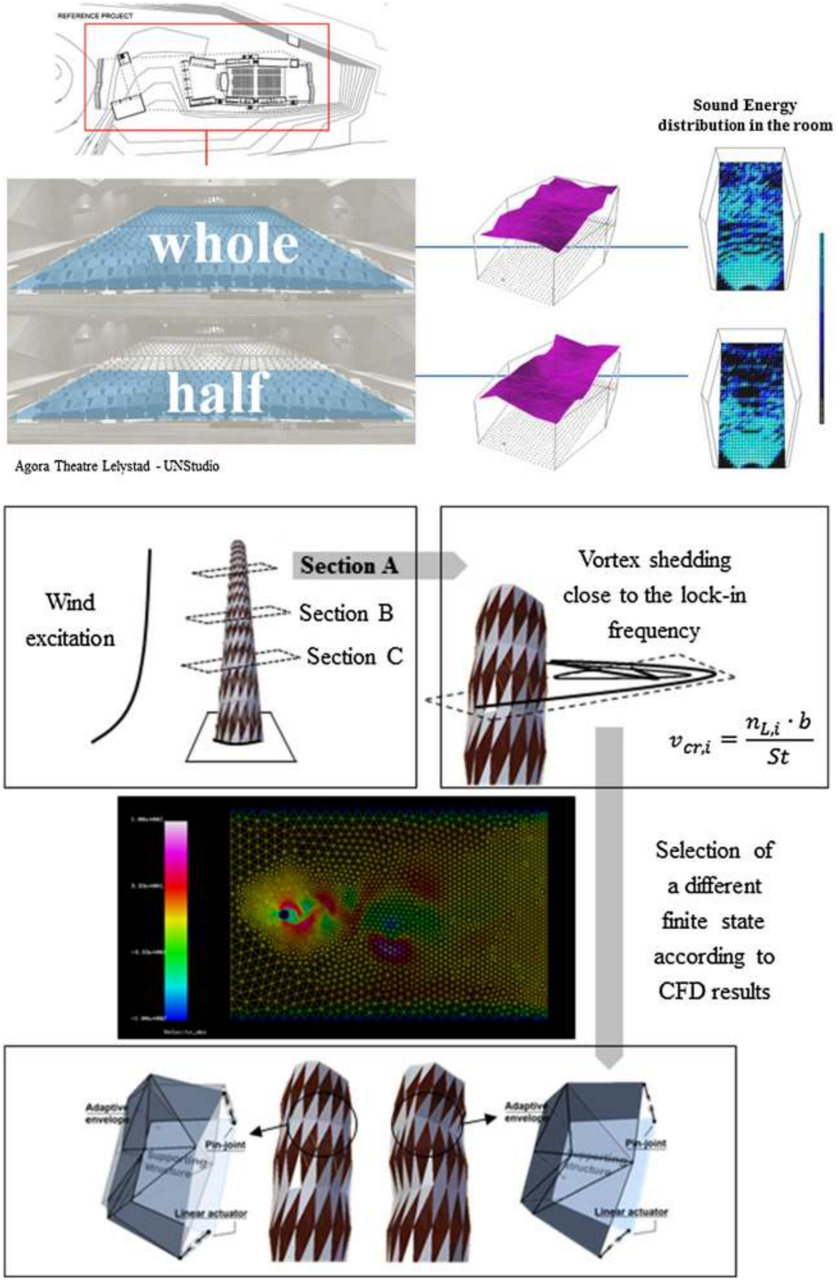

Figure 12. Conceptual visualization of the skin morphing process. (a) Adaptive ceiling of a concert hall and (b) adaptive building façade.

pressure in the initial impact phase and real-time control of valve opening, which leads to almost constant level of pressure during the entire collision process. The resultant decelerations are optimally reduced to 30% of the ones corresponding to passive response with locked valve (Figure 14b, where attention should be paid to different scale on vertical axis).

Several technologies applicable in various AIA systems are currently under development; namely, they are listed as follows:

- MR fluid-based shock absorbers [72]
- Piezo-valve based hydraulic/pneumatic shock absorbers [72,73]
- adaptive Inflatable Structures AIS [71,72]
- impactometer for online impact load identification [74]

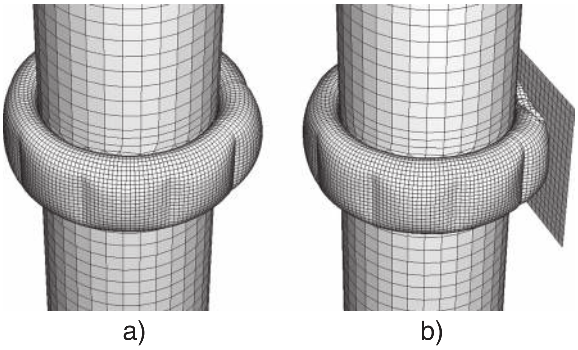

Figure 13. Pneumatic fender with Adaptive Impact Absorption system, protecting *off-shore* installation of wind turbine: (a) initial configuration and (b) deformation during collision.

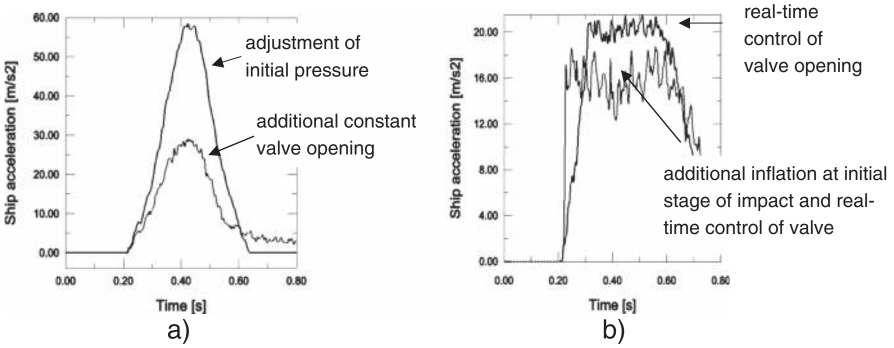

Figure 14. Numerical simulation results: (a) tuned initial pressure and tuned constant valve opening and (b) online controlled valve opening.

- various strategies of active flow control for pneumatic/hydraulic valves [73]
- various strategies of active control for online pressure release in AIS systems (eg. adaptive airbags) [71,75]
- systems based on multi-folding-snap-through effect [72,76]

Promising fields of applications currently under investigation are the following:

- adaptive crashworthiness systems for protection against transport collisions [73]
- adaptive fender systems for protection of civil structures against environmental impacts or terroristic attack [77–79]
- adaptive landing systems for protection of falling objects and people [69,72]
- optimal design of AIA systems [72,80–82]

4.3. Piezoelectricity for control and monitoring applications

Over the last decade, intelligent or smart structures have become prominent in the field of structural control and health monitoring; for a discussion of corresponding key technologies, we refer to Liu *et al*. [83]. A prominent example for putting smart structures into practice are piezoelectric transducers, which play an increasing role as sensors and actuators due to their light weight, good operating characteristics, and simple implementation on general components; see e.g., Preumont [84] and Moheimani and Fleming [85]. The research group at the Johannes Kepler University of Linz has conducted studies on piezoelectric structures with respect to electro-mechanically coupled modeling (see e.g., Vetyukov *et al*. [86] and Krommer *et al*. [87]), piezoelectric transducer design, and applications to structural control and health monitoring. In the present paper, we discuss two topics in some detail: (1) Passive and active structural shape control, and (2) structural health monitoring. In both cases sensor and actuator systems are put into practice by means of properly designed piezoelectric transducer arrays. We shortly summarize the basic concepts, review some related literature by the group, and conclude the subsection with new experimental results for a laboratory frame structure.

4.3.1. Passive and active structural shape control. Shape control is basically concerned with the computation of actuator distributions such that the actuated flexible motion of the body exactly coincides with the displacement field produced by an external force loading. For the case in which the external force loading is separable in space and time dependent functions, the solution to this *Dynamic Shape Control* problem can be easily found as follows. First, one must compute the quasi-static stress due to the spatial distribution of the external force loading and chose the spatial distribution of the actuation to coincide with this quasi-static stress. Second, the time variation of the actuation must coincide with the one of the external force loading. In contrast, if the time variation of the actuation is chosen as the negative time variation of the external force loading, the force induced motion can be identically eliminated in the whole body for all times. For a review of shape control, we refer to Irschik [88]. If the time variation of the external force loading is not known, passive or active control methods can be combined with shape control. The general idea for active shape control has been discussed by Krommer and Irschik [89], and applied to the control of torsional rod vibrations in Zehetner and Krommer [90] and of bending vibrations for plates in Zenz *et al.* [91]; in all these studies, piezoelectric transducers have been used. The use of passive shunt damping combined with shape control has been recently introduced by Schöftner and Krommer [92]. In the context of shunt damping, the piezoelectric transducers are used not only as actuators, but also as sensors.

4.3.2. Structural health monitoring. Piezoelectric sensors belong to the specific class of strain sensors for which the sensor signal is defined as a weighted integral of the strain over the domain that the sensors occupy. The weight functions constitute the spatial distribution of the sensors. The sensor design problem is to compute these weight functions such that the sensor signal has a desired meaning in terms of a kinematical quantity, which represents the work conjugate to a specific force quantity. The solution to this problem is sought as follows. First, one must compute the quasi-static stress due to the force quantities, with respect to which the signal represents the work conjugate. Second, the weight functions are chosen as this quasi-static stress. Proper choices of the force quantities enable the measurement of desired kinematical quantities; for a detailed overview see Krommer and Irschik [89] and for a recent review see Irschik *et al.* [93]. It is also worth mentioning that the sensor design problem is formally identical to the dynamic shape control problem, if the force quantities are chosen identical for the two problems; actuation and sensing are then collocated. Strain sensors in the previous sense are also known under the notion of spatial filters (as they filter certain spatial information. Examples are modal filters (Lee and Moon [94]), displacement filters (Krommer and Irschik [89]) and volume displacement filters (Preumont *et al.* [95]). Spatial filters are used for structural control and structural health monitoring (e.g., Deraemaeker and Preumont [96]), and they can be put into practice by piezoelectric transducers; e.g., refs. [94–96]. An alternative filter is obtained for trivial force quantities; in this case, the weight functions are not trivial in general, but the signal of the resulting sensor is, as long as the strain tensor is compatible. Hence, incompatible strains result into a non trivial signal. Such sensors are denoted as compatibility filters (Krommer and Irschik [97]), and the weight functions are denoted as nilpotent (Krommer and Irschik [89,97]). Because damage in many cases can be related to incompatible strains, the compatibility filters are proper candidates for structural health monitoring.

As an experimental example of using compatibility filters for structural health monitoring, we consider a three-story frame structure, to which three piezoelectric patches are attached to each of the six flexible sidewalls (see the center picture in Figure 15). This problem has been previously studied analytically and numerically by Krommer and Zellhofer [98]; yet, experimental verifications have not been published so far. For the three-story frame structure nine nilpotent weight functions exist, which correspond to the nine statically indeterminate bending moment distributions; the nilpotent weight functions are approximated by the piezoelectric sensor array. In the experiments, only six of the nine compatibility filters are put into practice by a parallel connection of the three piezoelectric

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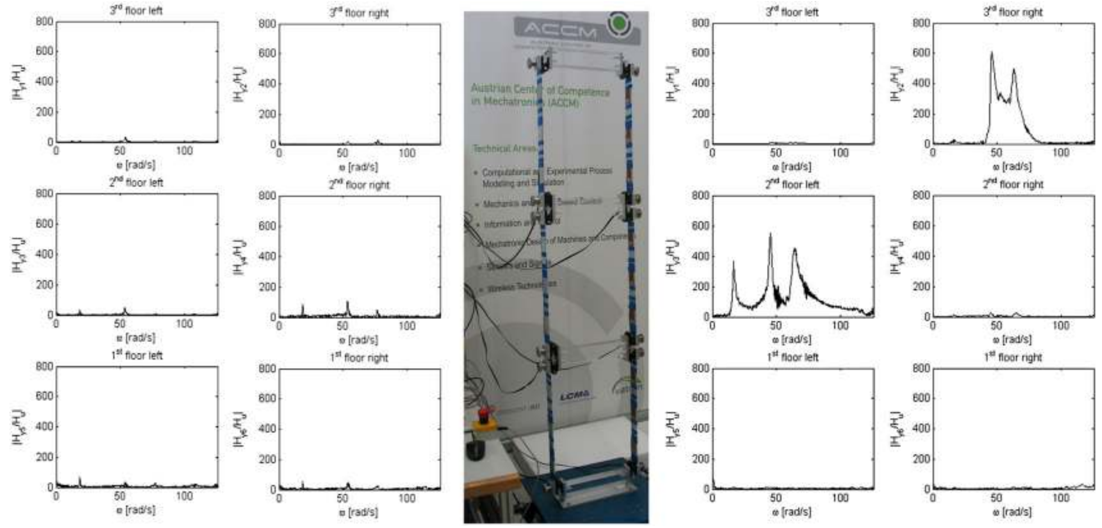

Figure 15. Three-story frame structure: response from undamaged structure (left), photograph of laboratory set-up (center), and response from damaged structure (right).

patches attached to each of the six sidewalls. Damage is introduced by changing the connection between the sidewalls and the rigid floors from a rigid connection to a hinged one. The amplitude response spectra of the measured signals are shown in Figure 15. The response from the undamaged structure is shown in the left two columns; one can observe a very small signal level. In contrast, the response for the damaged structure, which is shown in the right two columns, has a much higher signal level for two of the sensors. These two sensors correspond to the left sidewall of the second story and the right sidewall of the third story, for which damage has been introduced. We conclude that compatibility filters can be used to detect and localize damage very well.

5. SUMMARY OF THE IDENTIFIED KEY ASPECTS

Recent catastrophic earthquakes have provided the test-beds to verify the actual performance of seismically isolated structures and those equipped with devices exploiting different structural control strategies. The response of seismically isolated buildings has shown satisfactory results in terms of structural integrity. Nevertheless, a better understanding of the long-term behavior of this type of structures is needed. Furthermore, the application of such a technology to existing buildings is still very limited due to both physical and political constrains. In recent years, the task of avoiding excessive base displacements in seismically isolated structures has been tackled by proposing the combination of passive base isolators and feedback active or semi-active controllers (applying forces to the base), thus giving rise to the concept of 'smart base isolated' structures.

When passive devices for ED are added to the structure, common issues to be investigated include the estimate of their performance under seismic actions of different intensities, their optimal placement, and the formulation of efficiency measures. Dissipative strategies based on the relative motion of adjacent structures were shown to be particularly effective not only to mitigate the pounding effects and the seismic response but also to limit the energy transfer between the two substructures, thus avoiding the concentration of vibrations in the most vulnerable one. The interstructure passive damping elements can be combined with local feedback semi-active control systems implemented in the substructures.

Shifting to semi-active or active control strategies offers the possibility not only to further improve the seismic performance of a structure but also to widely broaden the applicability field, by being able to cope in an adaptive manner with different sources of external excitation than the seismic one, such as wind, traffic, and pedestrians load. Furthermore, the re-centering capability at the end of a severe event is desirable. The typical hysteretic behavior shown by civil engineering structures during these events is commonly represented by applying the control laws to properly modified versions of the Bouc–Wen model.

On the basis of the experience gathered in Japan from the actual implementation of active control systems in high-rise buildings, the recorded lack of actuation during severe earthquakes suggests the development of new technologies different from actuators of hydraulic type, together with the adoption of control strategies which are very robust with respect to both actuators failure and uncertainties. The latter observation yield, in recent years, to the proliferation of decentralized control methods which are particularly suitable to handle the large and complex systems typical of civil engineering. Furthermore, such a requirement can also be met by resorting to hybrid control strategies. Practical implementations aspects include the adoption of wireless data transmission, which represents a first step to move toward a fully digital technology aiming to replace all the analog components.

Waiting for the necessary technology to become available, several studies were developed to investigate different adaptation techniques and their applicability to civil engineering structures. Vibration control of wind turbines is a new and developing area of research mainly with the increased size and flexibility of rotor blades, and tower interactions. New architectural frontiers see a building envelope, which is adaptable to the external actions of wind, sunlight, or to the internal sound by means of a folding origami scheme and a finite states control strategy. The compelling demand of increasing the structural safety of key strategic assets make the adaptive impact absorption systems appealing for protecting civil structures against environmental impacts or terroristic attack. Finally, the actuating and sensing capabilities offered by properly designed piezoelectric transducers are reviewed with reference to passive and active shape control and structural health monitoring applications. In particular, continuously distributed strain sensors, the so-called spatial filters, which can be realized by piezoelectric sensors, are widely used for structural monitoring and control. The novel concept of compatibility filters has been experimentally tested for structural health monitoring of a three-story frame structure.

6. CONCLUSIONS

This paper was prepared to identify common trends and novel advances in the field of structural control research and applications to civil engineering. The main outcome is to provide a joint perspective on the topic from several scientists and their research groups across Europe. It is worth mentioning that, by no means, we intend to entirely represent the research community in this field and that many different activities are currently ongoing at a very large number of other European research centers, which we do not attempt to report herein. The auspice is that this work might prompt similar initiatives to be taken in the future, with in mind the final goal of enhancing the integration needed in order to establish a paradigm for this discipline.

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