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Immediate Seismic Resilience of a Controlled Cable-Stayed Bridge

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Abstract

Resilience issues have multidisciplinary relevance and, in recent years, attracted the interest of the scientific community. Within civil engineering sciences, resilience has been often recognized as an attribute of structures with respect to the outcomes of extreme events.

Control systems that can adapt to different loading levels can be exploited when structural conditions change due to local failures to offer a contribution to structural resilience. The innovative aspect is related to how the devices features are changed in real time to improve the loss of functionality function, which is at the base of resilience. When the parameters change occurs in real time, on line with the occurrence of a local failure, the concept has been formerly presented in the existing literature as "immediate resilience", along with a new measure index of resilience.

Immediate resilience theory is herein reviewed and underlined with reference to a new seismic case study, coming from a control benchmark, for which strategies for recovering after a damaging event the initial performance of the controlled bridge are presented.

Keywords: Resilience, Multidisciplinary, Earthquakes, Control, Recovery Function

1. Introduction

Active and semi-active control systems enjoy the common feature that can adapt themselves to different loading levels. This aspect can be exploited when structural conditions change, e.g. due to local devices failures, to offer a contribution to structural resilience by changing the devices working parameters of the survived devices and, thus, compensating performance losses of the control system.

The concept of resilience is transversal to several disciplinary domains, even though with different definitions that are, nevertheless, somewhat related (see e.g. the definition of Resilience as an ability "to recover from or adjust easily to misfortune or change" [1], or the British Standard [2] definition of Resilience of an organization as its ability "to anticipate, prepare for, and respond and adapt to incremental change and sudden disruptions in order to survive and prosper").

Resilience of a structure is similarly understood, with an highlight on the time aspect inherent to recovering: structural resilience is a general measure of the capability of a structural system "to provide a defined level of functionality over a given period of time". According with the MCEER framework [3], Resilience (*R*) is defined as the complement of a normalized measure of loss of functionality of a system over a defined control time period. The loss of functionality is measured by the residual functionality (by giving the value of the functionality function $Q(t)$) of the system at time t with respect to its capacity at some reference time (usually right after completion). Therefore, resilience is a structural trait related to performance in the case of occurrence of an extreme event.

Resilience in seismic engineering is said to possess four dimensions [3]: Robustness, Redundancy, Resourcefulness and Rapidity. Robustness is the structural system trait related to the capability to withstand a given level of stress, or of demand, without suffering great degradation or loss of functionality. Robustness can be measured by the value of the functionality function, right after the potentially damaging event. Redundancy is the capability to use alternative resources when the principal ones are insufficient or missing. Therefore, in a structure, redundancy is the existence of alternative load-paths (e.g. duplication of components). Rapidity is the trait related to how fast the functionality of a system is restored after the damaging event. Resourcefulness is the capacity to react (to identify problems, establish priorities, and mobilize resources) before a damaging event in order to enhance resilience by preemptive actions. Some of such dimensions are also related: e.g. rapidity and redundancy are strictly connected to resourcefulness owing to the second can create the first ones which do not previously exist.

About the contribution to seismic resilience coming from structural control, this is mainly related to Robustness and Rapidity. In this work, the applicability of an automatic intervention is reviewed from an existing research [4] as the online change of the working parameters in the semi-active devices. Special attention is payed to Rapidity by looking at the time interval required for mitigating losses incurred in the control system due to damages during a seismic event. The Immediate Resilience concept [4] is also stressed within the selected case study of a cable-stayed bridge control benchmark.

Since, in spite of some notable proposals, the concept of resilience is still a matter of discussion within the civil engineering community, and a codified framework is still lacking, a brief review of the meaning of resilience coming from different disciplines is presented to try to identify its base features and to better define and focus this issue in relation to structures.

This research paper presents also a discussion for spreading the concepts of seismic resilience, recently proposed within the structural control framework, to the typical structural members which can be able to recover functionality after damages in automatic-semi-automatic way (Immediate Resilience [4]). The positive outcomes coming from redundant and automatic systems are the key note to the proposed innovative approach, when local failures occur, providing on-the-fly compensation to performance losses.

2. Multidisciplinary view of resilience

As it is well known, the concept of resilience is adopted in a wide range of research fields, spanning from economic to social sciences, including also ecology and ecosystems. Notwithstanding such different developments and applications, some common issues can be identified. Resilience, for example, is usually related to a certain community, composed by social connections, but also to the more general connotation of ecosystem. This is markedly different from the meaning of resilience of an engineering structure, that can be defined also for the single structure.

Relations between social and ecological resilience are discussed in [5] where definition of social resilience is explained as the ability of groups or communities to cope with external stresses and disturbances as result of social, political and environmental change. This concept is often analyzed with respect to the resource dependency: the relation of communities whose livelihood and stability are direct function of their resources production and local economy. Side effects as mobility and migrations, stability and economic growth, distribution of income among population are identified as consequences of such dependency and, therefore, indicators of resilience. The complexity of studying resilience issues related systems are analyzed in [6] with possible approaches as well.

Three basic attributes of social–ecological systems are identified and discussed in [7] with interaction and implications as well. They are resilience, adaptability and transformability. Resilience and adaptability have to do with the dynamics of a system, or a closely related set of systems and communities. Transformability mainly refers to fundamentally altering the nature of a system. Four dimensions of resilience (the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks) are finally analyzed. They are latitude (the maximum amount a system can be changed before losing its ability to recover), resistance (the ease or difficulty of changing the system), precariousness (how close the current state of the system is to a limit threshold) and panarchy (cross-scale interactions - influences from states and dynamics at scales above and below). The effort of defining the dimensions of resilience has also been embraced in the civil engineering community (see e.g. [3]).

Coastal areas characterized of concentrated human population, and also sensitive to many hazards and risks from floods to disease epidemics, are specifically studied in [8]. As resilience, it mean the capacity of linked social-ecological systems to absorb recurrent disturbances such as hurricanes or floods so as to retain essential structures, processes, and feedbacks. Some examples from the real life are reported: in particular, it has been recognized how recurrence of disasters in certain areas have different impacts on the communities, in the restoration process in particular, with respect to different ones characterized by infrequent emergency events (e.g. Asian tsunami 2004).

Major parts of the works on resilience are focused on the capacity to absorb shocks maintaining function. In [9] another aspect of resilience that concerns the capacity for renewal, re-organization and development, is introduced as essential for the sustainability discourse, even if less in focus. This dynamic concept of renewal is also addressed in [10,11], where resilience is recognized as a process that leads to adaptation, not an outcome, not stability. This essential meaning is synthesized in the wide review of the existent literature in [10], where definitions, dimensions and indicators of resilience from different research fields are summarized, and the arising connections and differences recognized.

From the previous discussion, the concept of resilience is transversal in several scientific fields. In the civil engineering field, resilience is the property of an infrastructure to recover functionality after a damaging event. The next step will be the definition of a common terminology and framework for dealing with resilience issues.

3. Contribution of structural control to resilience and Immediate Resilience concept

Structural control solutions can contribute to resilience, meant as the property to recover functionality after a damaging event, firstly passively, by providing the system with robustness and redundancy. They can vastly reduce damage in the controlled structure and preserve the seismic response also after a strong, and otherwise damaging, event. Secondly, if of the active or semi-active type, they can adapt themselves to changing levels of loading, to different loading conditions or even to a change of the structural configuration (i.e. from intact to damaged, or from more statically indeterminate to less so). This readjustment of the control action, either in real time or, even if very short, over the period between two seismic events, aims at compensating the performance loss due to eventual failure of the devices, and is strongly related to rapidity.

This process of adaptation can happen at different time-scales, as recently recognized in [4]: on line with the dynamic excitation or, even if very short, in the period between two following loading events. The term "Immediate Resilience" [4] was used to identify the situation in which the original performance of the controlled bridge benchmark was rapidly recovered after failure of a device (see Fig. 1) by modifying the control parameters of the nearby ones in an automatic mode through a suitable semi-active law. This control law was termed the "one-shot" one to highlight that they will change their parameters only once per seismic event. Retrofit interventions can subsequently recover the undamaged configuration of the controlled bridge (a situation termed as "full resilience") by activating devices on purpose inserted in an ab-initio redundant set-up, or implementing new devices previously prepared nearby the structural system.

This concept is presented in the next section with reference to the seismic control solutions for a cable-stayed bridge, for which strategies for recovering after a damaging event the initial performance of the controlled bridge are presented.

Note that application of the concept to other structural member or typologies is possible as well, as it will be outlined in a subsequent section.

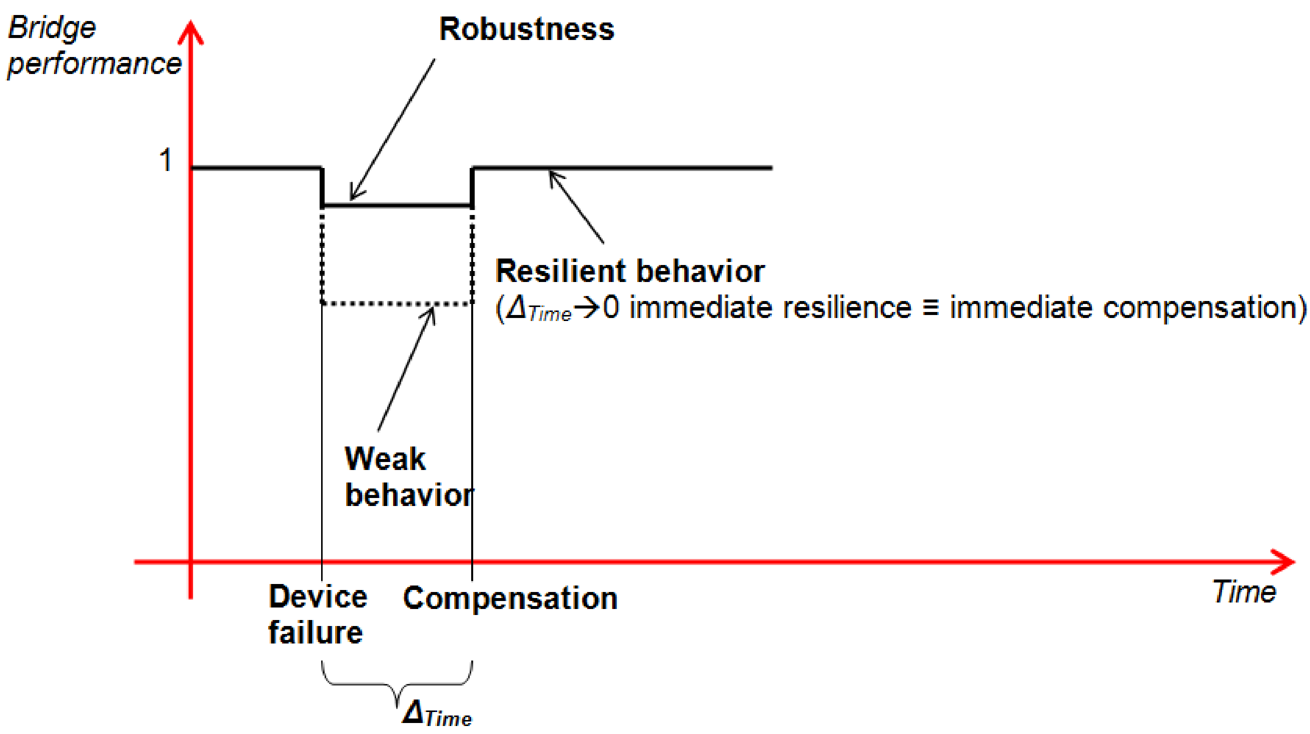

Fig. 1 – Example of Immediate Resilience (adapted from [4])

4. Assessment of Immediate Resilience on a Cable-Stayed Bridge Model

In this Section, the concept of "Immediate Resilience" is assessed in the case of the out-of-order state of some control devices assumed implemented on a cable-stayed bridge. The bridge object of the present study is the Bill

Emerson Memorial Bridge (Cape Girardeau - USA), spanning the Mississippi River. It is a fan-type cable stayed bridge (Fig. 2) with composite concrete-steel deck. The bridge was the subject of a well known control benchmark [4].

With respect to the original benchmark statement, the model has been refined within a multipurpose finite element framework introducing a some enhancements. The modifications consist in introducing soil-structure-interaction through the use of impedance functions, and in a richer model for the stays, moving from a single rod type representation (also called a one-element cable system) to a description with six rope elements for each cable. The resulting finite element mesh consists in about 2600 nodes and 2800 elements. A structural damping of 3% is assigned to the bridge model through the Rayleigh approach between the first and the sixth mode.

The studied control scheme is decentralized and comprises semi-active devices, able to change on line their working parameters, connecting the bridge deck to the piers and the bents. A total of 16 control devices, that act both in the longitudinal and transversal directions at 8 different positions, is adopted. The semi-active characteristics of the devices allow them to compensate in a very short time local out-of-services of members in the control system. The devices are implemented as a Bouc-Wen model, with parameters K=80000 kN/m, α = 0.02, $\beta = \gamma$ =40 m-1, $A = n$ =1, F_y = 1000 kN.

Numerical simulations for the case of seismic loading are performed on the version of the cable-stayed bridge model proposed in [12], consequently the seismic record has been applied to the bridge considering soil-structure interaction and accounting also for the time delay due to wave propagation from bents to the piers.

The bridge is assumed loaded by the effects of the strong seismic record represented by the well known El Centro one (Imperial Valley Irrigation District, substation in El Centro (CA), Imperial Valley California earthquake of May 18 1940, peak ground acceleration PGA of about 0.3g), which is often used in studies of structural control.

Resilience of the controlled structure is here evaluated with reference to the distribution of devices on the structure shown in Fig. 2. The control system is composed of semi-active devices operating in a passive control configuration. To simulate failure, the dampers working parameters are changed at the beginning of the analyses at positions (2T, 6T, 8T) along the bridge deck. This choice aims to maximize the loss of performance of the control system, and gives results very close to the ones obtained assuming a changing at the time the PGA is attained. Failure of a device is simulated by a total reduction of its stiffness (see [4] for details on the devices parameters).

In Fig. 3 the lateral displacement of the deck for the El Centro record, measured at the left bent, in Fig. 2 is depicted. Device 4T is compensating the out of service of the broken devices (2T, 6T, 8T) with a change of its working parameters. The parameters of the Bouc-Wen model employed when the device is compensating the loss of the other three are K = 80000 kN/m, α = 0.02, $\beta = \gamma$ =10 m-1, $A = n$=1, F_y=4000 kN.

Without compensation the transversal displacement becomes upsettingly large (about 0.5 m of relative displacement at the left abutment of Fig. 2). Instead, when device 4T compensates the out-of-service of the other devices the amplitude of deck vibrations is even less that for the case of no device failure. The longitudinal behavior has not been reported due to it does not show interesting modifications due to the inherent robustness of the control system in this direction, as already noted in [4].

It is worth noting that the recovery of functionality occurred immediately when the devices failed, according to the concept of “Immediate Resilience”.

Similar positive outcomes are even more evident in the case of stronger signals (such as the Gebze Tubitak Marmara Arastirma Merkezi, Turkey, on August 17, 1999) for which without compensation the transversal displacement becomes worryingly large (about 0.6 m of relative displacement at the left abutment) and pounding between Pier 2 and the bridge deck was also observed [4].

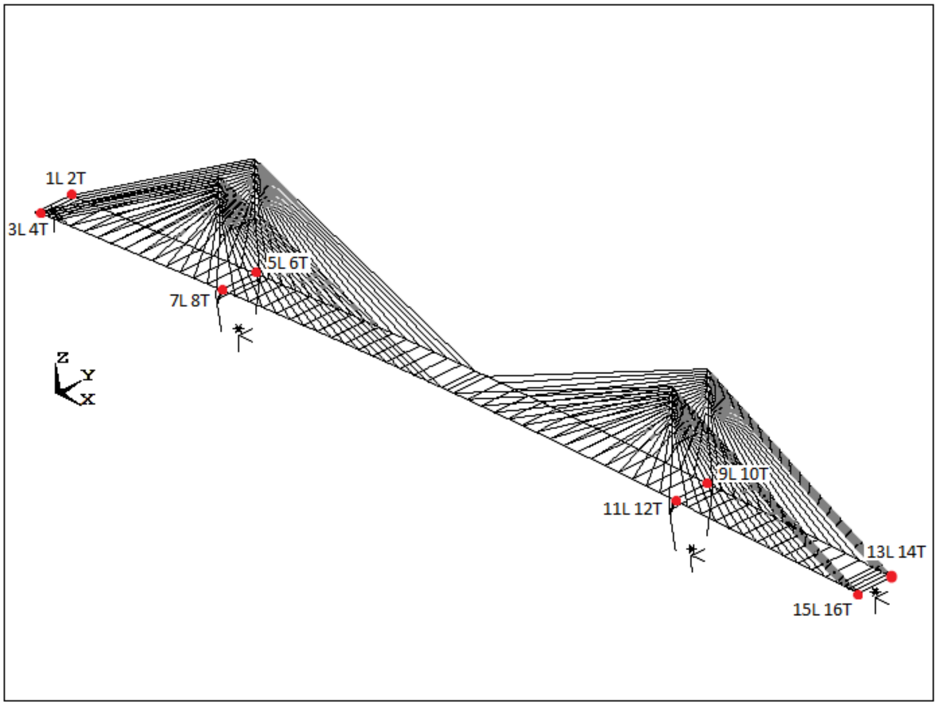

Fig. 2 – Structure under study with the control arrangement: T define a transversal device, L a longitudinal one

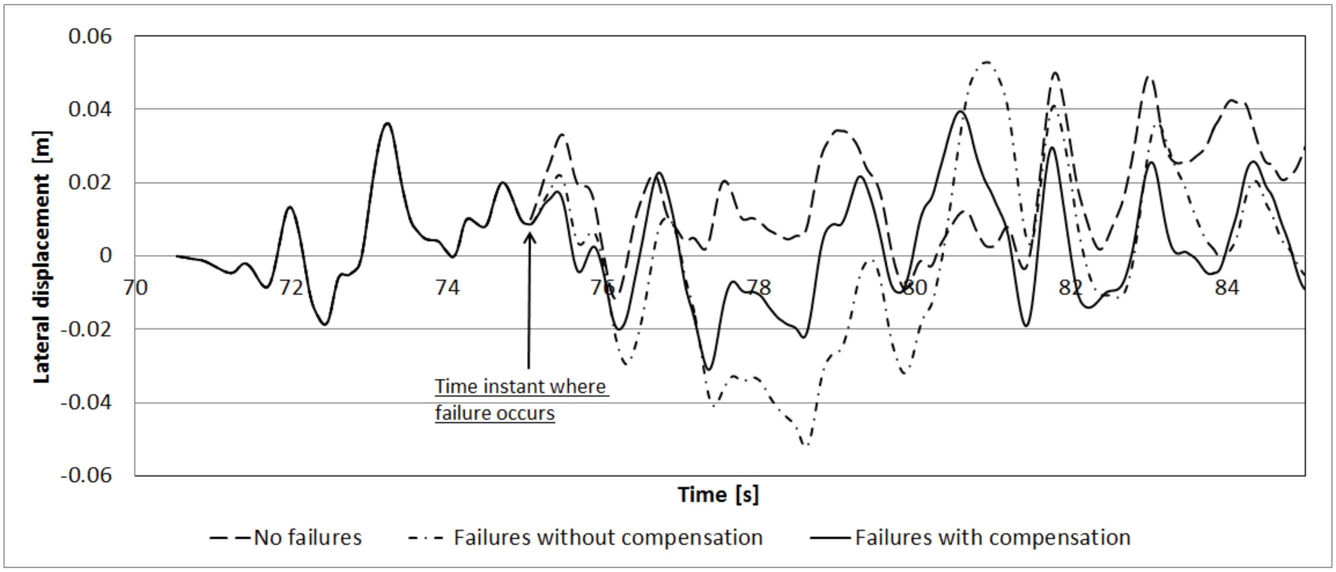

Fig. 3 – Lateral displacements of the deck at the left bent of Fig. 2

5. Application of Immediate Resilience to other structural cases

The concepts of seismic resilience can be also extended to other structural configurations besides the one previously considered related to the international bridge benchmark. The key aspects are related to redundancy and the capability of recovering functionality by modifying on-the-fly intrinsic structural parameters, such as stiffness or reaction forces. An example is application of this concept to precast structures.

A companion paper presents new jointed connections which make use of unbounded post-tensioned tendons to connect vertical and horizontal members together [13]. In that paper a numerical models is used reproduce experimental results with a focus on shear-rotation relationship, characteristic of unbonded post-tensioned precast concrete beam-columns connections, and prestress loss due to cyclic loading.

The design of prestressed structural systems composed of ductile connections is ruled within the Japanese Building Code. According to the allowed criteria: under Level 1 earthquakes (recurrent period of 50 years), connections among beams and columns have to behave as rigid joints and interfaces among them have to remain in compressive state, while under Level 2 earthquakes (recurrent period of 500 years) and Level 3 earthquakes (recurrent period of 1000 years), the connections can rotate elastically to prevent damage to beams and columns and a maximum drift of 1% and 2%, respectively, is expected for the columns. The tendons should be stretched up to 85% of nominal yielding strength at the prestressing introduction, and should not enter the plastic range under design earthquake loads. The frictional force produced at the beam to column interface by the prestressing strands has to transmit shearing stress to the column. Cyclic loading of the connections can reduce the prestress force and, as a consequence, the system could not resist the beams' dead load.

To overcome this potential problem, in [13] an a-priori limit on the prestressing loss was considered. In the framework of Immediate Resilience instead, one could monitor the prestressing strands and recover on-line the prestress losses by automatic tensioning of the strands.

6. Conclusions

Resilience is a multidisciplinary concept faceted in several definitions, from the capacity to absorb shocks maintaining function to the capacity for renewal, re-organization and development. It can be found in different fields: social sciences, economy, ecology and more recently engineering sciences. Development of earthquake resilience in particular has attracted the interest of the civil engineering community as an interesting attribute of structures with respect to the seismic hazard.

Control systems that can be able to adjust their working parameters to different loading levels can be exploited, when structural conditions change due to local failures, to offer an immediate contribution to structural resilience. Therefore, performance losses due to device failures can be compensated in an immediate way. This concept has been introduced as "Immediate Resilience" in the former literature, with a new index proposal for resilience measure as well. This introduces a penalty function that allows for a zero value of resilience once an acceptable recovery time is exceeded. Furthermore, the total resilience is gradually reduced with time passing through a suitable reduction factor.

This work firstly underlines immediate resilience theory with reference to a seismic case study coming from an international bridge benchmark. The satisfactory effect of semi-active control devices compensating the loss of other control devices is hihglighted and it was found that it was more prominent for stronger signal. The recovery of functionality occurred immediately when the devices failed, according to the concept of "Immediate Resilience".

The spreading of the concepts of immediate resilience, proposed within the structural control framework, to the typical structural members which can be able to recover functionality after damages in automatic-semi-automatic way, is finally proposed. The positive outcomes coming from redundant and automatic systems are the key note to the proposed innovative approach, when local failures occur, providing on-the-fly compensation to performance losses.

7. Acknowledgments

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