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EXPERIENCE WITH FRICTION DAMPERS IN NEW AND EXISTING STRUCTURES

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Abstract: *This presentation summarizes the experience gained over the last 15 years of using dampers in projects throughout Greece, in order to reduce the earthquake impact on structural and non-structural elements. Frictional dampers have been selected instead of the more common fluid viscous dampers, since they are independent of velocity, thus significantly facilitating preliminary design. The frictional dampers will also remain locked for low level seismic and wind excitations, so that movement will generally be associated to moderate or strong seismic events. The topics covered include analysis methodology, selection of dampers, quantification of energy absorption and detailing, with particular reference to the introduction of forces at the damper to structure interfaces. The sample projects involve both reinforced concrete and steel structures and correspond to new constructions as well as to strengthening of existing structures. The designs have all been carried out according to EN 1998 with peak ground accelerations of 0.16g and 0.24g. Importance factors vary depending on the project. In all projects presented, the major conclusion is that the use of dampers has led to a significant reduction in the design seismic forces. In the case of new constructions, this has allowed the use of reduced structural sizes. In the case of existing structures, the reduction in seismic forces effectively allows a building designed to lower acceleration levels to become resistant to current code seismic accelerations with minimal interventions.*

Evolution of seismic design

Earthquake resistant design has significantly changed over the last decades. Greece is a seismically active region, where most of the earthquake activity in Europe takes place. Although seismic awareness and damage records date from the antiquity, the first compulsory earthquake resistant design code in Greece came into effect in 1959. At that time there was little knowledge concerning seismic accelerations, due to the lack of records. Consequently, that code prescribed equivalent static load procedures with design accelerations ranging from 0.04g to 0.12g. A revision of the code was carried out in 1985, introducing dynamic amplification procedures and detailing rules. The deadly earthquakes of 1995 prompted the introduction of a new, fully revised code, along the lines of EN 1998 with three peak ground acceleration regions ranging of 0.12g, 0.16g and 0.24g, which were revised to 0.16g, 0.24g and 0.36g in 2001, with most of the country assigned to the 0.24g acceleration. This range of accelerations is valid today under EN 1998.

As can be easily understood, a design acceleration in the order of 0.04g to 0.12g directly applied to the structure is completely different from a peak ground acceleration range of 0.16g to 0.36g with its accompanying dynamic amplifications combined with significance factors and soil factors. The situation today is that the majority of existing structures have been designed for earthquake actions which are close to an order of magnitude lower that the current seismic design requirements.

Earthquake resistant design is currently being carried out using the capacity method. This means that a certain level of controlled structural damage is assumed permissible, thus allowing the reduction of the seismic design accelerations to account for the seismic energy consumed in the damaged zones. The stability of the structure is to be ensured through the provision of overcapacity to critical members (e.g. columns). The underlying logic for this methodology is to reduce the associated construction costs, while maintaining an overall acceptable safety concept, since the damaged buildings will allow safe evacuation. There are however four main issues with respect to this design concept:

1. The average owner is not aware of this philosophy and expects a code compliant building not to be damaged during an earthquake.

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2. A major earthquake event is always followed by a series of aftershocks of reduced but possibly still significant intensity. Consequently, a structure that has developed plastic hinges within the framework prescribed in the capacity design procedure, and has therefore been safely evacuated, is particularly vulnerable to an aftershock.
3. Existing buildings designed according to older codes can not possibly satisfy the requirements of capacity design. Attempts to upgrade them to current acceleration levels and capacity detailing rules often essentially lead to the need for rebuilding them.
4. The capacity design is based on a safe evacuation principle. The safety of an industrial structure however is associated with its ability to allow the continued operation of the plant following a major earthquake and not with its safe evacuation. Consequently, as far as the owner is concerned, a design carried out to the letter of the code does not protect an industrial structure.

Industrial structures present further complications with respect to the requirements of capacity design. For example, the “strong column – weak beam” principle can not be satisfied in structures where the beams carry significant operational loads, while the column dimensions are restricted by process requirements. A characteristic example of such a predicament occurs in the internal structure of a natural or forced draught cooling tower, where the columns need to be as slender as possible in order not to hinder air flow, while the beams carry the internal water fill and distribution loads over large spans due to the aforementioned requirement of keeping the column sizes and number to a minimum.

The limitations of the seismic capacity design outlined above, along with the increase in peak ground acceleration levels prescribed in the codes have led to the need for an alternate method to provide the requisite seismic safety to special structures.

Seismic dampers

The use of mechanical devices in order to reduce the seismic effect on buildings is relatively well understood and established, although still exempted from many national and international codes. Dampers are an indispensable part of this approach, since it has long been realized that the increase in the natural period offered by base isolation needs additional displacement control in order to arrive at practical solutions.

There are two distinctly different seismic damper types. Fluid Viscous Dampers (hereafter FVD) were the first commercial dampers to be used and are based on the resistance provided by a viscous fluid confined inside a metal cylinder and circulating through orifices in a piston following seismic displacements. Friction Dampers (hereafter FD) are based on the conversion of kinetic energy induced by seismic motion into heat through friction from special contact surfaces.

Figure 1. Damper types. Left: FVD (Taylor Devices, 2018), Right: FD (Damptech, 2018).

In the course of the investigations carried out over several years, it was decided to use a specific type of frictional damper: a bidirectional frictional damper developed by Damptech (Damptech, 2018). The reasons are briefly outlined hereunder.

1. FVDs are velocity driven. The damper force is expressed by the relationship $F=CV^{\alpha}$, where C and α are damper constants and V is the piston velocity. This requires knowledge and control of the velocities at specific locations. It also means that the forces developing at the damper will vary depending on the earthquake. On the other hand, FD forces are independent of velocity and will be constant (after slip) for all earthquakes. From a designer’s point of view this constitutes a major advantage, since it facilitates preliminary design, while detailing may be carried out independently of the earthquakes selected to govern the project.

2. Since FVDs are velocity driven, they are generally always active, thus corresponding to a flexible joint and possibly affecting the overall operation of the building. On the other hand, FDs are locked for forces below their nominal capacity and will only be activated at slip. Consequently, small seismic excitations and smaller lateral loads, such as wind, will not activate the dampers.
3. Since the FVD is velocity driven, the force-displacement relationship is not linear and typically results in an elliptical hysteresis loop. On the other hand, the bi-linear behavior of an FD will result into a rectangular hysteresis loop, which essentially means that the energy dissipated (i.e. the area enclosed by the hysteresis loop) will be larger.
4. FVDs are by definition linear elements. On the other hand, the bi-directional rotational FD offers a significant versatility, since seismic movement is rarely axial.

The basic form of the bi-directional frictional damper is shown in the following photo. The damper capacity may be increased by adding damping disks and by controlling the pretensioned bolt.

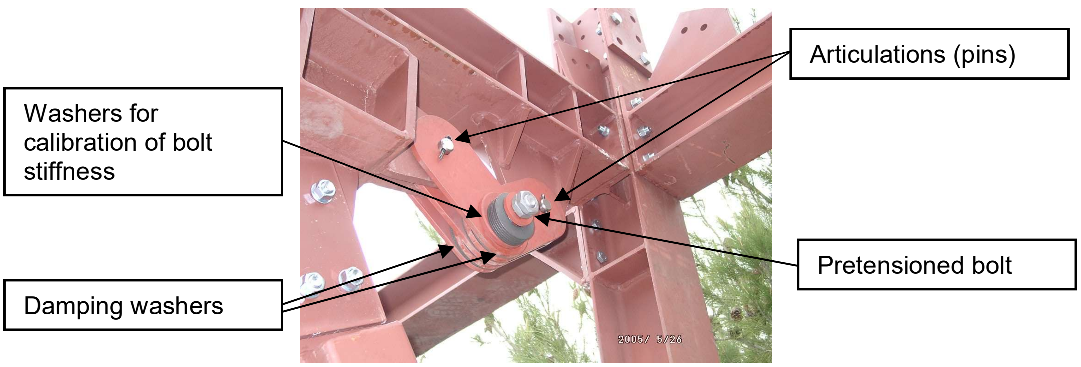

Figure 2. Bi-directional friction damper. Basic form.

Designing with dampers

Despite the obvious advantages of using dampers in the seismic design of structures, most codes either do not provide any guidance or simply exclude them. It is consequently usually up to the designer to formulate an acceptable design procedure. Dampers are non-linear elements and their use in a seismic design will necessarily involve a series of non-linear time history analyses. In order to remain within the time and budget constraints of ordinary design projects, the following methodology has been developed.

1. Carry out a preliminary conventional analysis, in order to ascertain the need for the use of dampers. Not all designs require dampers and at least an elementary cost-benefit investigation is required as a first step. This analysis is usually an equivalent static analysis.
2. Once dampers have been deemed beneficial, a strategy for their location needs to be developed. The situation is relatively straightforward in a base isolation system, but becomes more complicated in a complex structure, particularly when the project involves rehabilitation and strengthening of an existing building. A typical procedure would be to introduce ordinary elements at the envisaged locations. These elements will be assigned the dampers' "locked" stiffness. A further series of analyses will provide the forces developing in these elements and their participation in the total seismic force system. These analyses may be either equivalent static analyses or response spectrum (modal) analyses, depending on the structure.
3. On the basis of experience concerning the energy dissipation capacity of the specific damper type to be used, the structure is analysed again introducing the expected energy dissipation as an equivalent behaviour factor. This factor is calculated approximately as a weighted percentage of damper element participation to the total seismic force system using a conservative energy dissipation assumption. These analyses will typically be response spectrum analyses and will lead to the dimensioning of the structure.

4. Carry out a series of non-linear time history analyses in order to confirm the assumed energy dissipation. The friction dampers are modelled according to the Bouc-Wen theory (Bouc, 1971 and Wen, 1976). At least 3 acceleration records will be required and particular care must be given to their selection and possible scaling. Since little, if any, guidance on the selection of the accelerograms is provided in the applicable codes, this procedure will necessarily be based on experience and on literature (for example, Bommer and Acevedo, 2004). For practical and overview reasons, these time history non-linear analyses are usually carried out on simplified models.
5. Carry out any required fine tuning of the design, following the results of step 4.

Due to the significance of step 4 above, some further remarks are provided. Clearly, the choice of accelerograms is important to the outcome of the analysis. The first choice in this respect is whether actual recordings or synthetic records will be used, assuming that (as is usually the case) no specification in this respect is included in the project design basis. The use of synthetic (artificially generated) accelerograms for a project in a seismically active region is not recommended, since, presumably, sufficient records should be available. A more realistic approach results from using as many actual recordings as possible and averaging the key response parameters, instead of scaling. The following figure depicts the acceleration response spectra of some of the major earthquake recordings in Greece, plotted against the code defined elastic design spectrum for the peak ground acceleration corresponding to the majority of the Greek territories (0.24g).

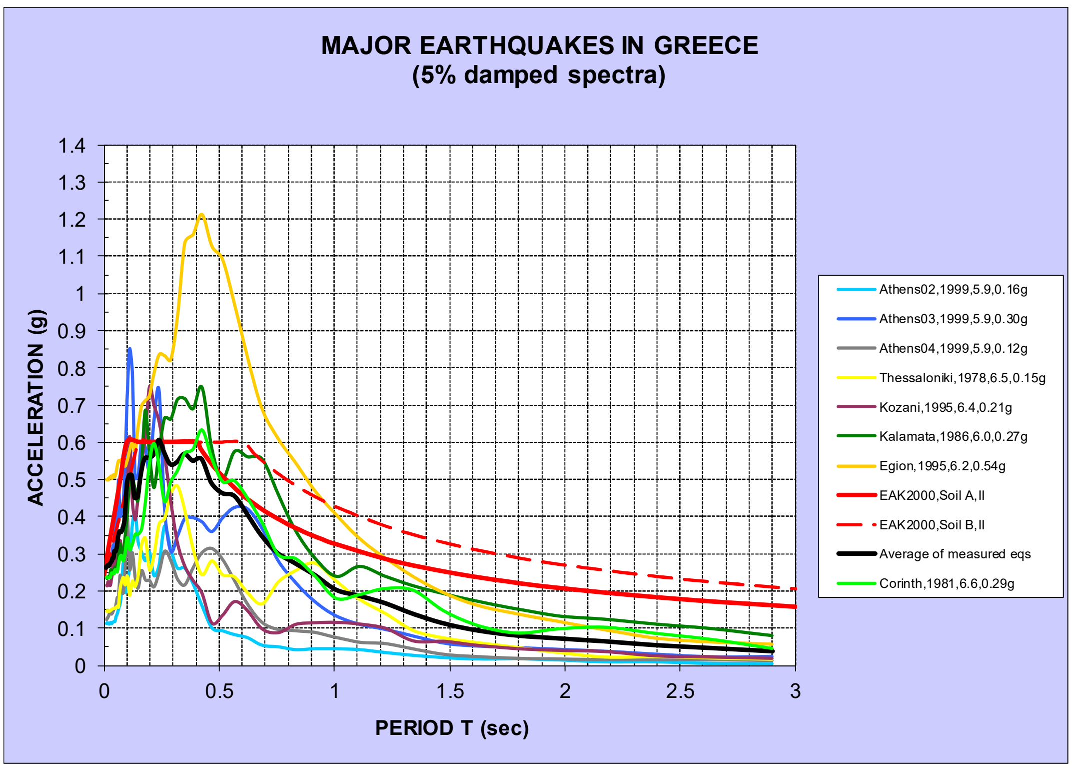

Figure 3. Response spectra from major Greek earthquakes. In red: Code elastic design spectra for 0.24g peak ground acceleration.

Since, the use and interpretation of accelerograms in an actual design is rather subjective, it is preferable to base the work on actual recordings and average the results (possibly excluding extreme minima or maxima), rather than relying on fictitious data.

From a purely computational point of view, it is suggested to keep the time step to a value that will facilitate convergence and experience has shown that a value below T/25 (where T is the structure's natural period) is a reliable initial approach. The duration of the recording to be used in the time-history analysis depends on the available resources, but 10 sec centered around the peaks should be a minimum requirement.

Some software allow control on the building of the stiffness matrix. In such a case, a diagonal matrix should be the initial choice, in order to accelerate the exploratory and calibrating investigations. In the interest of an efficient investigation of the forces and corresponding displacements developing on the dampers, the remaining structure should be modelled as simply, yet as realistically (from the point of view of stiffness and mass distribution) as possible. Surfaces requiring extensive finite element meshes may lead to an increased number of eigenvalues for satisfactory mass participation and may introduce convergence difficulties in the time steps. It needs to be kept in mind that these analyses are by nature qualitative and that the intended outcome is the order of the energy absorption that can be achieved for a given earthquake and a given damper arrangement.

Since the objective is to maximize the energy consumption in the dampers, these devices should be allowed to displace sufficiently. In other words, if a structure will not develop significant deflections under linear seismic loading, then dampers will probably not be worth the effort. And, correspondingly, if a structure can be made to accommodate larger displacements, then dampers would effectively reduce seismic forces.

In the following sections, examples from past projects will be presented in order to outline the advantages offered through the use of these damper types.

Residential building (2004)

This has been our first experience with dampers and it involves the addition of two floors to an existing two-storey reinforced concrete building. The existing building had been designed according to the old code with an equivalent seismic acceleration of 0.12g and its design included a provision for an additional concrete storey. The owner wanted the final structure to be compliant with a 0.16g peak ground acceleration according to the current code. The use of steel structures combined with light partition and wall elements for the superstructure, along with the energy dissipation provided by the dampers, allowed the final product to fulfil the owner's requirements.

Figure 4. Residential building. General view of damper bracing and dampers detail.

Multi-level car park (2010)

The project involved a 7-storey car park to be built outside the Main Terminal Building of the Athens International Airport. The dimensions of the building are 200m×70m×23m and the peak ground acceleration was 0.16g with an importance factor of 1.15. The owner and the architects required the minimization of any visual obstruction, other than the parked cars. Consequently, at the start of the project, shear walls were excluded, while the number of braced bays were to be kept to a minimum. Given the weight of the concrete slabs and the parked cars, the seismically active mass was significant and could not be handled without a prohibitive increase in the size of the respective bearing elements. It was consequently proposed and accepted to use dampers for the reduction of the seismic energy.

Figure 5. Multi-level car park at the Athens International Airport.

The procedure outlined earlier was followed for the design of the structure, the main body of which was divided into 3 structurally independent parts separated by joints. The reinforced concrete staircase towers have been designed as emergency stoppers in case of excessive accelerations. The time histories of 4 acceleration records from actual Greek major earthquakes have been used for the design of the dampers.

The following figure shows a typical damper connection detail at the bracing junction and a snapshot from the non-linear time history analysis depicting the energy absorption achieved by the dampers.

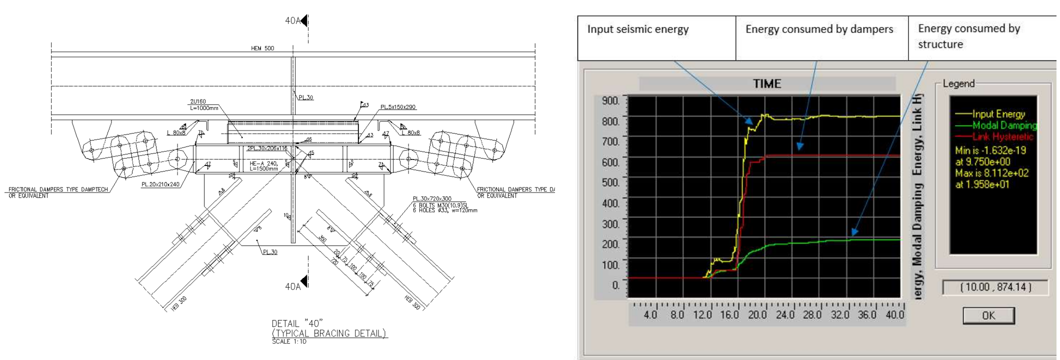

Figure 6. Multi-level car park. Left: Typical damper connection detail. Right: Energy absorption time history for the Thessaloniki 1978 earthquake acceleration record (from Damptech).

Filter installation on top of an existing silo (2006)

The project involved the installation of a dedusting unit on top of an existing reinforced concrete silo. The silo has a total height of 40m and had been designed according to the old code, with an equivalent seismic acceleration of 0.12g. The owner wished that the silo be reinforced in order to withstand the seismic impact of the new installation (total of 165 tons) on the roof according to the requirements of the current code (peak ground acceleration: 0.24g). The project was near

Patra and the seismic risk was significant. The water body seen in the photo below corresponds to the Corinthian Gulf, one of the most active seismic faults in Greece.

It was decided to use a base isolation system combined with friction dampers, since reinforcing the silo would be costlier and access to the foundation was difficult. For this reason, a rigid steel platform was erected on top of the silo roof, supported by elastomeric bearings. Bidirectional horizontal friction dampers were installed between the platform and the reinforced concrete silo walls. The dedusting facility, consisting of a filter, a motor and a chimney, was placed on top of that platform. Uplift restraining vertical bars were arranged on the outer circumference of the silo.

The project was executed in 2006 and on June 08, 2008 a magnitude 6.5R earthquake hit the region (focal depth: 3 km). Significant damages were reported in the built environment and the recorded peak ground acceleration was in the order of 0.19g. Another earthquake of magnitude 4.9R occurred in 2011. The support system has behaved satisfactorily and no damages or excessive displacements have been observed in the superstructure or in the silo.

Figure 7. Dedusting installation on top of an existing silo. General view of rigid platform (left) and detail of friction damper (right).

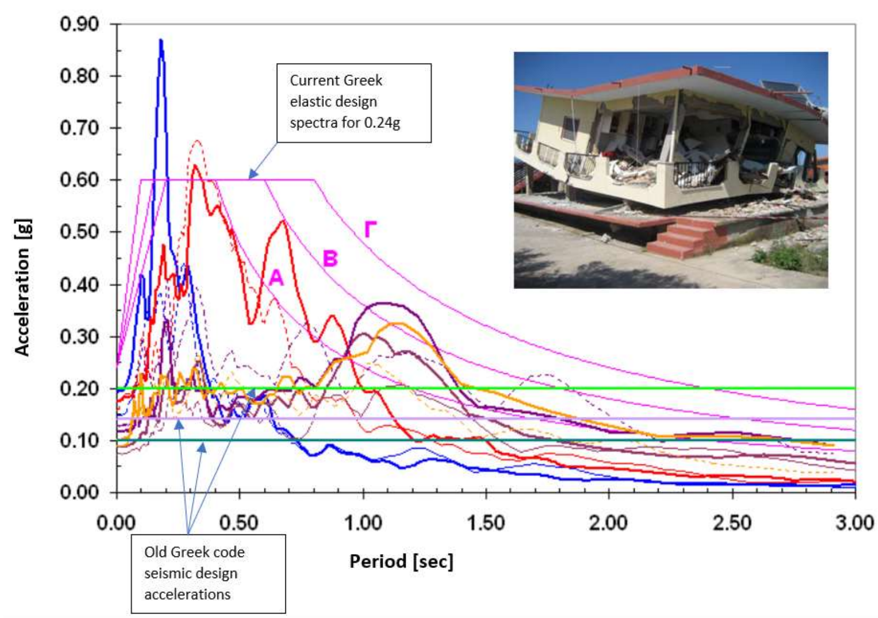

Figure 8. Patra region earthquake (08.06.2008): Response spectra from motion records compared to current Greek elastic design spectra and Old Greek Code design accelerations. Inset: Collapse of 2-floor reinforced concrete frame building during the main shock.

Figure 9. Completed dedusting installation on top of an existing silo. General view (left) and support platform (right). Photos taken in 2011.

Heavy industrial filter (2005)

The project involved the installation of a heavy industrial filter on top of a reinforced concrete frame. The constraints which led to the use of dampers were the significant mass of the filter (780 tons), the limitations on foundation size imposed by neighbouring buildings and the requirement for freeunobstructed heavy truck passage under the concrete frame which practically limited the size of the concrete columns and beams. There were also a number of underground utility lines (cable and pipe channels) which further restricted the dimensions of the foundations. The use of dampers resulted in a reduction of the seismic loading at the top of the concrete frame in the order of 60%, thus allowing the use of smaller sizes for the concrete elements and eliminating the need for a foundation overhang.

An inspection was carried out in 2017 (12 years after the completion of the project), and the condition of the dampers was found to be satisfactory.

Figure 10. Installation of heavy filter with geometrical constraints. General view (left) and braces with dampers (right).

Force transfer at damper locations

In analogy to the detailing of joints in a capacity design, the connections of the dampers to the structure should ensure that the connection remains elastic during damper slip. In other words, the connection should possess an overstrength with respect to the damper nominal capacity. This is easier fulfilled in new constructions, but requires careful considerations in cases where the damper is connected to an existing structure. In particular, it needs to be checked whether the existing structure can accommodate the local concentrated forces and that it possesses sufficient overstrength.

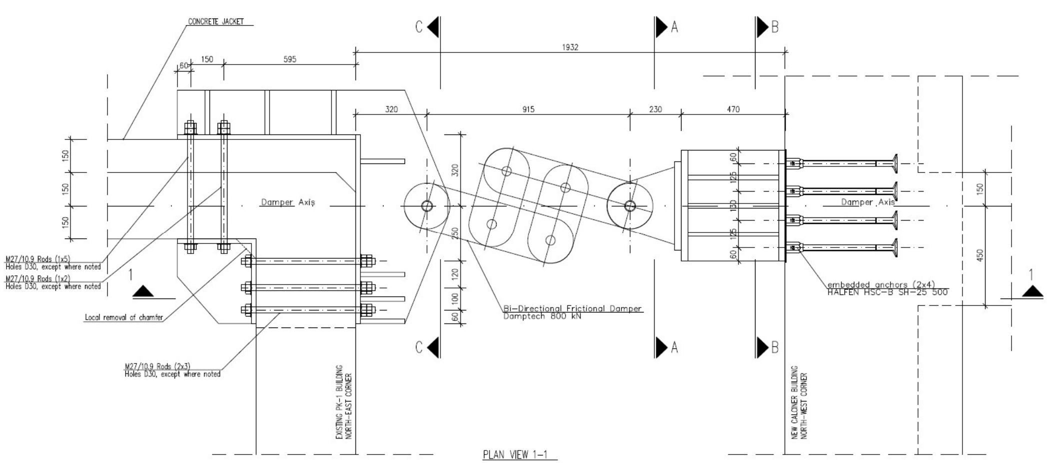

Figure 11. Connection of damper to structure. Existing structure (left) and new structure (right).

The figure above depicts a case involving dampers being used between an existing reinforced concrete structure and a new one, which is used to assist in the seismic behaviour of the existing structure. In the case of the new structure, the reinforcement in the new structure is arranged in a way that allows the concentrated force from the damper anchorage to be introduced into the structure. In the case of the existing structure, additional measures need to be taken (here in the form of an additional concrete jacket) in order to ensure that the anchorage force can be introduced and transferred further into the existing structure.

Conclusions

The use of dampers results in a significant reduction in the seismic energy to be absorbed by the structure, which practically translates into lower design forces for the structural elements. The disadvantages mainly lie in the absence of specific guidance and rules in the existing standards, which often leads into uncertainty from the part of the client or owner. From that point of view, damper solutions are usually proposed for cases where traditional design techniques can not be applied, due to geometrical, operational or constructional restrictions.

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