Review of damage-tolerant solutions for improved seismic performance of buildings

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Abstract. Building structures have been designed for more than 40 years to protect life in the event of a major seismic event. In order to achieve this goal with a minimal initial investment, structures are designed, using the ductility principle, as sacrificial systems, undergoing significant plastic deformations in the main structural elements, which progressively deteriorate. If in the design codes the structural damage is to some extent explicitly accepted and quantifiable, problems related to non-structural damage are addressed much more vaguely. This no longer meets market and society requirements. New structural systems are needed, which are not only efficient in reducing structural and non-structural damage, but also offer good re-centring capability, durability, reparability and affordability, accompanied by accessible design methods. This paper reviews the principal solutions that can be used to achieve these goals. Their advantages and limitations are analysed, as well as their potential as damage tolerant structural systems.

1. Introduction
In performance-based design, designers are supposed to demonstrate that a structure meets specific performance criteria set in advance. Generally, these criteria, as set forth in the 1967 SEAOC “Blue Book” [1], state that the structure must: (1) resist minor earthquakes without damage; (2) resist moderate earthquakes without structural damage but some damage to non-structural components; (3) resist major earthquakes with substantial structural and non-structural damage; and (4) resist the most severe earthquakes without structural collapse. Yet, most modern seismic design codes address these principles only partially and in a greatly simplified manner.

The main objective of modern seismic design codes, like Eurocode 8 [2], is to safeguard life in the event of a major earthquake through dissipation of energy by the development of inelastic deformations in dissipative components. Limitation of damage to non-dissipative (brittle) components, as well as enhancement of total energy dissipation by a global plastic mechanism is promoted using capacity based seismic design of non-dissipative components. Thus, the protection of life at the Ultimate Limit State (ULS) is ensured with the cost of sacrificing the structure in the case of rare, high intensity earthquakes. In the case of more frequent, lower intensity earthquakes (Serviceability Limit State – SLS), the code limits inter-storey drifts, which is intended to control the damage to non-structural elements. However, limitation of structural damage is not addressed at SLS. This design approach has the following
disadvantages: (1) the repair of structural damage experienced under a major (ULS) earthquake is not addressed; (2) at the SLS only the non-structural damage is addressed (in a simplified manner).

The need to change the design philosophy towards solutions that are damage tolerant has been highlighted by recent earthquakes such as Christchurch, NZ [3-6] and L'Aquila, IT [7]. The experience of these earthquakes has highlighted that although several structures behaved as designed and damage mechanisms have protected human lives, the associated costs were significant, many buildings being demolished because the replacement cost was lower than the repair cost.

In this context, one very effective way to achieve the desired performance while protecting the structural and non-structural components is to reduce the seismic response of the structure using base isolation and/or viscous dampers. Although this method is very effective and it was successfully applied in the past for some projects, it has a major drawback: it is very costly. This high cost starts with the design stage and ends with the maintenance of the building. First, this kind of solution usually requires very advanced and complex calculation, often including dynamic nonlinear analyses, which are not yet accessible for current design practice. Second, the devices used are very expensive as they are in general subject to patents, and they require testing for prequalification. Third, these systems generally require constant maintenance and some of them require also external power and other data acquisition and interpretation equipment. Therefore, this approach has become more of a niche solution, adopted in general for high profile investments, or where other solutions are not providing the required performance.

Alternatively, a simpler way of reducing the repair costs and minimize the damage to the buildings structural and non-structural components would be to localize the inelastic damage within bolted fuse elements [8, 9], capable to dissipate the seismic energy, that can be replaced after a strong earthquake and which can also afford the structure re-centring capabilities when properly designed. Although this idea is not new, today in Europe there are very few buildings designed on this principle. Following the international trends, extensive research was carried out in Europe during the last decade, leading to the introduction of several innovative steel-based systems [10]. However, only a few designers are confident enough to employ these systems, as provisions for their design have not been included in the Eurocode or other national design codes.

Another important factor limiting the adoption of damage-tolerant structural systems is the insufficient explanation of the basic seismic design principles to the owners and to the general public. Because they are unaware of the potential for damage in a building that complies with the present minimum code requirements, they are less interested in the use of such systems, even though the initial cost difference between the two solutions would be minor compared to any repair costs in the event of a significant earthquake.

2. Main criteria for damage tolerant structural systems

Damage-tolerant structural systems must be able, on the one hand, to reduce the seismic response of the structure in order to limit both structural and non-structural damage, and on the other hand they must be designed to allow the "reset" of structures with minimal cost. This "reset" consists in maintaining or restoring the stiffness and resistance of the structure, the energy dissipation capacity, and finally, in the re-centring of the structure. In other words, the main objective of the damage-tolerant systems is to limit the damage to structural and non-structural components, and to allow the quick and cost-effective return of the structure to its pre-earthquake state.

This general objective must be translated into several clear assessment criteria, which will indicate the optimum solution for a given project. We propose the following five criteria:

- efficiency of damage reduction;
- re-centring capability
- reparability
- durability
- affordability
The first criterion relates to the ability to prevent or reduce the damage to structural and non-structural components of the building. To limit both the direct and the indirect effects of the earthquake on non-structural components (NSC), the system must limit both the maximum inter-storey drifts and maximum story accelerations. As far as the structural components are concern, the system needs to be assessed both locally and globally. For example, systems with dissipative elements placed at the ends of the frame beams allow replacement of parts that have exceeded the elastic stress level (an advantage over conventional systems). However, in the condition in which a floor damage occurs, requiring difficult and expensive repairs, the efficiency of these systems at the global level is greatly diminished.

The re-centring capability is also very important and refers to the ability of the structure to return to the initial undeformed shape after the removal of the damaged dissipative components. Buildings with residual displacements may no longer be acceptable, not only for safety reasons, but also for functionality and comfort reasons. More often, the necessary works to bring the building back to a non-deformed shape may be impractical.

The reparability refers to the ease of bringing the system back to its initial state by repairing or replacing damaged components and the associated cost. In general, the use of less encapsulated systems should be favoured, where state assessment, repair or replacement can be made as simple and as cost effective as possible.

The durability refers to the lifetime, maintenance and possible protective measures required, depending on the sensitivity of the system to environmental actions. If a building has a standard life span of 50 years, components of damage-tolerant systems should also have a similar lifetime. Some devices, such as friction dampers, are particularly sensitive to potential problems with water infiltration. Polymer-based systems have potential problems with the aging of component materials. Therefore, it is essential to provide for a maintenance and monitoring system. It is also advisable to design the structure so that, even in the event of a failure in some of the integrated dissipative systems, it will be able to resist a certain level of lateral load.

The affordability is perhaps the most important factor from a market perspective. It relates to both the initial cost and the maintenance cost. These costs must be balanced against the benefits of the system in terms of reducing the potential repair costs and the downtime following seismic events during the life span of the building. The analysis should therefore cover the entire life cycle. Clients must understand that such an analysis involves much greater effort in the initial concept phase, with higher design costs associated with this phase. An informed decision about the optimal solution can result only based on an accurate assessment of the costs and benefits.

3. Seismic response control systems
Damage limitation during an earthquake is not a new concern. Although, in theory, the damage limitation can be achieved for structural components by increasing the resistance of the structure and designing an elastic seismic response, this approach is not an economical solution, nor does it ensure the limitation of the damage to non-structural components. In general, this goal is achieved by reducing the seismic response of the structure. This is obtained by using devices specifically designed for this purpose, that can be classified, based on the type of control, in passive, semi-active, active and hybrid systems.

Passive control systems consist of mechanical devices to dissipate and reduce the induced seismic energy in the structure, thus reducing structure response and possible damage [11]. They cannot, however, adapt to the overall response of the structure. They are optimized to protect the structure from a specific dynamic load but have limited efficiency for other cases and other types of dynamic loadings [12].

Semi-active control systems are adaptive and can adjust their behaviour based on the information collected about excitation and structural response [13]. The components of this system include sensors, a control computer, a control actuator and a passive damping device. The sensors measure the excitation and / or structural response. The control computer processes the measurements and generates control
signal for the actuator, which then acts to adjust the passive device behaviour [11]. Their efficiency is limited by the maximum capacity of the passive devices on which they are based [14].

Depending on the measurement of the global system response, active control systems can have optimal efficiency compared with passive control systems, which depends on the local responses only. Active control systems require significant energy to counteract the dynamics loadings, which cannot be ensured during severe natural hazards due to failure of the energy supply during such events. Moreover, active control systems are complicated; they require sensors and controller equipment and give a shift in the dynamic behaviour of the structure by adding or removing energy from it; this may result in an unwanted or even unstable condition [15].

Hybrid control systems introduced since the 1990s represent the parallel grouping of passive systems with semi-active or active systems to achieve the benefits of both hybridized techniques and to greatly mitigate the limitations of each technique. Hybrid devices have a higher efficiency than a passive system and are more reliable and require less energy than active devices because there is no need for large control forces [12].

The extent to which structures containing one or more such systems qualify as damage-tolerant structural systems should be assessed in terms of meeting the five previously proposed assessment criteria.

Passive control systems emerge as the most likely candidate for the role of energy-dissipation in a damage-tolerant structural system. They also offer several advantages that make them particularly interesting: they present intrinsic stability, do not require an external source of energy, do not require structural response measurement to function, have low design, deployment, and maintenance costs [11-13], [16].

Passive control systems can also be roughly classified into two main categories: (1) base-isolation; (2) energy dissipation devices.

4. Base isolation

Base isolation is a passive structural control technique that uses a series of elements interposed between the foundation and the structure to isolate it from the vibrations induced to the foundation by the seismic action. The effect is to increase the structure's fundamental periods, possibly combined with energy dissipation. Base isolation is suitable for both new structures and the protection of existing buildings [3-7]. Such systems have been used for over 50 years both in buildings and bridges [17].

One of the main limitations of this technique comes from the way it works. Such systems are less effective for flexible buildings, whose base un-isolated period is already quite large. Also, in seismic areas with high amplification in the area of large periods, the efficiency of these systems is reduced. Another limitation is related to the fact that isolators are efficient in reducing the horizontal components of the seismic action but are not effective for the vertical component of the seismic action. Some of the most commonly used isolation systems devices can be classified in two categories: isolators who rely on elastomeric materials to provide the recentering force (elastomeric bearings, lead-rubber bearings, combined elastomeric and sliding bearing) and those that do not (sliding friction pendulum systems).

4.1. Isolators based on elastomeric materials

Initially, elastomeric bearings were made up of large blocks of natural rubber without additional reinforcement. Subsequently, horizontal steel plates were added to improve the behaviour and vertical stiffness, and synthetic rubber started to replace the natural rubber. These isolators offer a low damping rate and are generally used with additional damping devices.

Lead-rubber bearings are similar to the elastomeric ones, having in addition a lead core pressed into a vertical bore. This core undergoes plastic shear deformations, dissipating energy with a very stable hysteresis. The composition of the rubber has also undergone changes over time, with the goal of increasing durability and damping, which has led to the elimination of the need for additional damping devices.
In a combined elastomeric and sliding bearing setup, friction-based isolation systems account for sliding at the interface between two materials. One of the materials is usually stainless steel while the other material is usually a polymer. Initially, the latter was Teflon, and more recently synthetic materials specifically developed for this purpose, of the high-density polyethylene type. The efficiency of these devices is influenced by factors such as temperature, wear, slip speed, surface pressure, and degree of contamination of the friction surface. In these systems, the entire vertical force is supported by the friction interface, which also provides hysteretic energy dissipation, while the re-centring force is provided by neoprene elements that do not take up vertical loads. The main advantage of these systems is the low cost.

In general, the primary drawbacks of this category of isolators relate to the dependence on the properties of elastomeric materials, which limits their lifetime and the applicability under severe environmental conditions (especially low temperatures).

4.2. Sliding friction pendulum systems
The friction pendulum isolators combine the horizontal sliding motion with a re-centring force provided by the sliding surface geometry. They consist of an articulated element sliding on a concave spherical surface. The lifting of the building mass, which takes place during lateral movement, ensures the re-centring force. These devices have several advantages: good energy dissipation ability, stable behaviour, reduced torsional effects in the structure, simplicity of calculation, very good durability and very low maintenance costs. They also don’t require fire protection, and the sliding surface can be protected against contamination by relatively simple means. Among the drawbacks are the high manufacturing cost, the impossibility of taking up vertical tension forces and the lifting effect of the structure.

5. Energy dissipation devices
There are many devices capable of absorbing energy and increasing the damping of buildings to reduce the seismic response. These additional dampers are used especially in high-rise buildings that cannot be effectively isolated. In these flexible buildings, it is necessary to control lateral displacements, which can be achieved by using damping devices that absorb much of the seismic energy. These systems can also be used in combination with base isolation systems to supplement their energy dissipation capability. The most used types of systems are hysteretic devices, viscoelastic devices, self-centring devices and dynamic vibration absorbers.

5.1. Hysteretic devices
As can be seen from their name, these devices dissipate energy through a mechanism that is independent of the load rate. They can also be divided in two groups: metallic dampers, using metal plastic deformation to dissipate energy, and friction dampers, which use dry sliding friction between two surfaces to dissipate energy in the form of heat [18].

Metallic dampers provide a very efficient energy dissipation mechanism. They have very good durability, very stable properties over time, are relatively insensitive to temperature variations and have low cost. Their main disadvantage is the limited number of load cycles and their nonlinear response.

Friction dampers have good performance, being able to dissipate a large amount of energy. They are less affected by the load frequency, the number of load cycles and temperature variations and exhibit rigid-plastic behaviour. Among the disadvantages are the variability in time of the friction coefficient, mainly influenced by the condition of the friction surface, which is affected by the environmental conditions, and the fact that these devices do not dissipate energy at forces less than the friction force. Such dampers are generally installed in vertical bracing.

One of the devices tested at the University of Canterbury on steel frames is the high-force-to-volume (HF2V) lead extrusion dissipater [19]. Due to their small size and high capacity these devices can be used as dissipaters in concentrically braced structures, or in beam-column moment connections.
5.2. Viscoelastic devices
This category includes a wide range of devices with an energy-dissipating mechanism dependent on the rate of load. The damping force in these devices is proportional to velocity, and the behaviour is viscous. These can be classified into two main categories: solid viscoelastic dampers and liquid viscoelastic dampers.

Solid viscoelastic dampers are usually made from copolymers or glassy substances that dissipate energy through shear deformation in the viscoelastic material. During these deformations, the viscoelastic material manifest features of both elastic solid and viscous fluid, returning to its original shape while dissipating energy as heat.

Viscoelastic fluid dampers are based on the dissipation of energy using the properties of a viscous liquid, which can be contained in an open or closed container. Examples of these dampers include [18]: (1) the cylindrical pot fluid damper, (2) the viscous damping wall system (VDW) and (3) the fluid viscous damper.

In examples (1) and (2), such a device uses an element attached to the top of a structure level which is forced to travel through a high viscosity material contained in an open container attached to the lower side of the structural level. The shape of this container may be cylindrical or parallelepipedal. The advantage of such a device is the very high energy dissipation capacity and relative constructional simplicity, while the main drawback lies in the need to use a very high viscosity material, and such materials have both frequency and temperature dependent properties.

In example (3), the damper is based on the flow of a fluid into a closed container. The movement of a piston forces the fluid through small holes instead of deforming the fluid locally, resulting in high levels of energy dissipation. The main advantage of this type of damper is its ability to reduce both the deflection and stress at the same time, since the damper force is totally out of phase with the stresses resulting from the structure flexing. Moreover, these dampers are practically insensitive to temperature variations. A main disadvantage is the difficulty to reduce the peak structural response in the initial stages of loading due to the dependence of the damper’s resisting force on the velocity.

5.3. Dynamic vibration absorbers
This type of device, also known as tuned mass damper, is used to reduce energy dissipation demand on the structure under dynamic loading [18]. This is done indirectly by transferring a part of the vibration energy to an absorption device. The main characteristics of the system are mass, rigidity and damping. Its dynamic properties must be tuned to those of the main structure. The applicability of this type of device for seismic actions is limited due to detuning that may occur by changes to the dynamic properties of the structure caused by plastic deformations.

6. Self-centring systems
This type of systems possesses a native re-centring capability due to small residual deformations after load removal [18]. In general, they are based on some type of pre-stressing obtained either with a pressurized fluid or with a pretensioned spring or cable.

Recent development of performance-based design recommendations for self-centring moment resisting frames (SC-MRF) [20] was motivated by results obtained in the last decade in experimental and analytical investigations of these systems for seismic applications. Research shows that these ductile systems resist structural damage after repeated inelastic response cycles under design-level earthquakes. Due to posttensioning that enables self-centring, residual drift after an earthquake is eliminated. Supplemental connection elements are designed to minimize structural damage in the main frame elements at inelastic levels of cyclic loading, and to provide stable energy dissipation through yielding, or through friction-based damping.

The same principle can be applied not only in conjunction with post-tensioning to MRFs, but also to columns base [21] and centrically braced frames (CBFs) [22] using gravity as the restoring force.

Shape memory alloys (SMAs) have been employed to develop various types of SMA-based braces [23-25] and beam-column dissipative connections [26].
Shape memory alloys are a class of materials that can recover from large strains through the application of heat (known as the shape memory effect) or removal of stress (known as the superelastic effect). This results in several unique characteristics, including Young's modulus-temperature relations, shape-memory effects, superelastic effects, high damping characteristics, and re-centring capabilities. SMAs have demonstrated energy dissipation capabilities, large elastic strain capacity, hysteretic damping, excellent high/low-cycle fatigue resistance, re-centring capabilities and excellent corrosion resistance, as in figure 3. All of these characteristics give SMAs great potential for use within seismic resistant design and retrofit applications [27].

In general, the disadvantages of SMA devices are the high cost given by the complexity and the low energy dissipation capacity. Also, varying environmental temperatures may have certain influence on the SMA behavior, and, the transformation temperature must be lower than the working temperature to ensure super elasticity.
7. Damage-tolerant structural systems
The basic concept underpinning these structural systems is the use of replaceable dissipative elements combined with a re-centring solution for the structure [28].

They are generally made up of two structural subsystems: the vertical (gravitational) load resisting system, and the seismic force resisting system. The gravitational system is designed to remain elastic and also to provide the elastic re-centring force, while the lateral resisting system utilizes affordable and easily replaceable or reparable structural devices or elements that ensure both the seismic energy dissipation by concentrating the plastic deformations as well as supplementing the rigidity of the gravitational structure to lateral displacements.

In general, both base-isolation and specially designed energy dissipation devices are represented by complex integrated systems developed by a few specific manufacturers, often protected by patents, which also require testing and validation, and which introduce significant costs both in the design phase as well as the construction stage of the structures that incorporates them.

Therefore, innovative steel-based devices, consisting of engineered solution made from simple, design-specific, non-patent-protected structural elements, that generally do not require additional approval, designed as an integral part of the structure, represent the ideal solution for damage-tolerant structures.

Depending on the general setup of these devices, relative to the main gravity structure, their stiffness and the stiffness of the main structure can be described in a simplified way as serial or parallel springs. Considering the need for an elastic re-centring force in order to ensure the re-centring capability of the structure, only the parallel setup present a viable solution, as it is the only one that retain the stiffness of one system while the other is removed.

Also, the total stiffness of the structure is increased by the addition of the dissipative elements in the parallel setup, while in the serial setup this is decreased.

Such a structural setup is called a dual system, due to its two subsystems: one that is flexible, behaving elastically and a second one that is rigid, behaving inelastically.

The elastic, flexible subsystem can be implemented as a moment frames, that can undergo large elastic deformations.

The rigid, inelastic subsystem can be implemented as a braced frame incorporating bolted, easily replaceable fuses.

Some authors [9, 28] proposed a damage-tolerant structural system based on EBFs with bolted replaceable links, figure 4, and re-centring capability.

The weaker, more flexible subsystem (MRF) should provide a minimum strength (25% of the total seismic force [29, 30]), using the equation below.

\[ F_{y}^{MRF} \geq 0.25 \cdot (F_{y}^{MRF} + F_{y}^{EBF}) \quad (1) \]

The re-centring capability should be validated by keeping MRFs in the elastic range and constraining plastic deformations to replaceable dissipative members until reaching the ultimate shear deformation in links. This can be done analytically (predesigned using formulas below [31], level by level.

\[ \delta_{u}^{EBF} = \delta_{y}^{EBF} + \delta_{pl}^{EBF} = \frac{r_{y}^{EBF}}{K_{y}^{EBF}} + \frac{e}{L-e} \cdot H \cdot \gamma_{pl, u} < \delta_{y}^{MRF} = \frac{r_{y}^{MRF}}{K_{y}^{MRF}} \quad (2) \]

Where \( \delta_{y}^{EBF} \) is the yield storey displacement of the EBF, \( \delta_{pl}^{EBF} \) – the plastic storey displacement of the EBF, \( K_{y}^{EBF} \) - the EBF stiffness, \( \gamma_{pl, u} \) – the plastic deformation capacity of the link, \( K_{y}^{MRF} \) – the MRFs stiffness, \( e \) – length of the link, \( H \) – the height of the frame and \( L \) – the span of the frame.

Considering that the analytical approach is a simplified one, nonlinear static and/or dynamic analyses are recommended in order to confirm the re-centring capability.
Another damage-tolerant system was based on dual steel frames with replaceable steel shear panels, figure 5 and re-centring capability. In this case the bracing system was represented by the steel shear panels [32].

These can be also made replaceable while the re-centring force is provided by the parallel elastic moment frame.

Replaceable moment resisting friction connections are conceived to develop the dissipation mechanism by means of the relative slip into ad-hoc devices located between the lower beam flange and the outer cap plate connected to the column flange, while the upper flange of the beam is connected to a plate either bolted or welded to the column, figure 6 [33].

The randomness of the friction properties has to be as much as possible mitigated and accounted for in the design phase, because this variability can inflict in the joint response and, consequently, the global behaviour of the structure. This type of approach is more difficult to implement is high seismic areas because in order to provide re-centring capability this system must be coupled in parallel with an elastic, more flexible subsystem.
8. Conclusions
The state of art for damage-tolerant structures system was reviewed by briefly summarizing the principles of such systems and principal qualifying criteria. Also, the principal types of structural control systems and devices were reviewed to assess the potential use in damage-tolerant structures; these include: (a) passive; (b) semi-active; (c) active; and (d) hybrid systems. To demonstrate the damage-tolerant structural systems potential and future directions in civil engineering, an overview of some innovative practical implementations of these systems was provided. The state of art clearly indicates the huge capability for these systems and their importance in modern buildings. These systems can be used to reduce the damage induced by earthquakes and to allow for easy and inexpensive re-centring of the structures. Further research will address a parametric analysis of efficiency of different damage-tolerant solutions in reducing both structural and non-structural damage.

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