

# Quantifying resilience of damage-resistant technologies: framework for enhancing New Zealand's bridges seismic performance.

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**ABSTRACT:** Loss of functionality on road networks during the Canterbury earthquakes (2010-2011) questioned New Zealand's established seismic resilience. Excessive direct and indirect costs due to downtime and non-structural damage highlighted the need to move towards new performance indicators. Resilience holds the key to describe performance of modern structures since it demands a system that shows: reduced failure probabilities, reduced consequences from failures and reduced recovery time.

This paper, firstly, aims to overview the current research on seismic resilience to horizontal infrastructure and the existing damage-resistant technologies. Secondly, it presents a framework towards the quantification of seismic resilience of damage-resistant technologies for bridges. The framework is based on a probabilistic recovery analysis and includes analytical modelling and low damage design, in conjunction with fragility and costs assessments at the structure level. Finally, future research to be undertaken is proposed, which will center into the application of the presented framework by selecting different New Zealand bridges as case studies.

Combining the concepts of resilience directly with structural forms and performance indicators will increase the confidence in implementing low damage technologies as a method for reducing damage to bridges in an earthquake. Translating resilience measures into concise and meaningful terms to decision makers, such as closure times and final costs, will lead to a better understanding of the benefits of mitigation.

## 1 INTRODUCTION

An engineering approach that focusses solely on the concept of life-safety will not ensure resilient structures nor communities. To achieve truly resilient structures, bridge earthquake engineering needs to embrace a modern definition of seismic risk that considers a number of important factors such as financial losses associated with repair, disruption to business and the time to reinstate services and activities. Therefore, a new more general design methodology is proposed, resilience-based design (RBD), which can be considered as an extension of performance-based design (PBD) which is just part of the total design effort (Almufti & Willford, 2013). The goal of RBD is to make individual structures as resilient as possible, by developing technologies and actions, as will be discussed shortly, that allow each structure to regain its function as promptly as possible.

Several bridge systems have been developed by past research to reduce construction time, minimize seismic damage and increase reparability in comparison with the conventional cast-in-place construction. Damage-resistant technologies such as seismic isolation have been addressed by past research, and low damage technologies for bridges have been developed and experimentally validated (White & Palermo, 2016; Chegini & Palermo, 2015). In fact, the first project, Wigram Magdala Bridge, to use low-damage connection details on a bridge in New Zealand, and possibly worldwide, was successfully finalized in the previous year (Routledge et al., 2016). Aim of low damage technologies on bridges is to reduce and control damage to a structure by developing ductile joints which uses self-centering and energy dissipation; consequently, a very limited level of damage is expected in the structural elements which are maintained in the elastic domain.

This paper introduces a framework for RBD of bridges which combines enhanced structural design with organizational and ambient considerations, recognizing that resilient design and planning is the

key to achieve a truly resilient structure. Finally the framework presents the quantification of resilience, in terms of functionality, costs and recovery times, as a method to evaluate the success of a resilient design. Finally, a RBD approach will also facilitate the communication of risk and seismic mitigation measures to owners and decision makers.

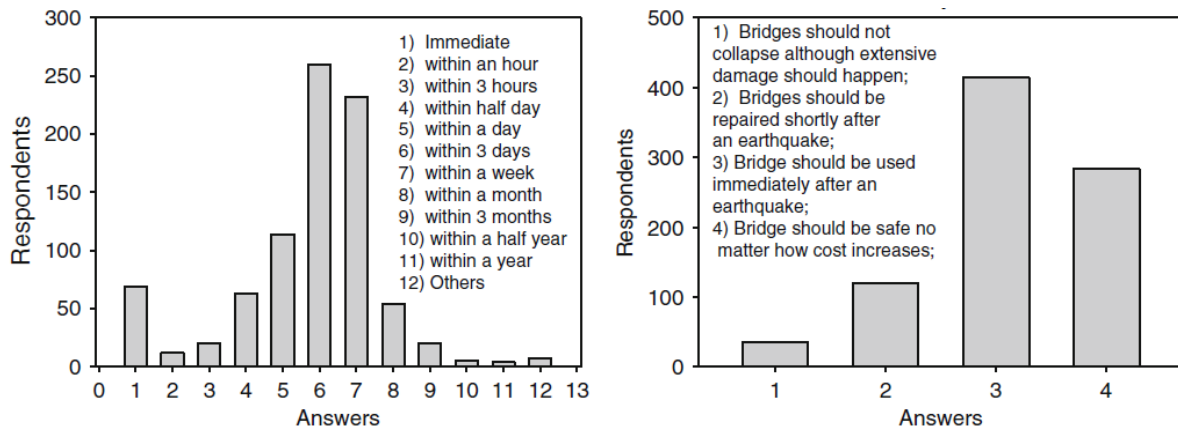
## 2 RESILIENCE-BASED DESIGN

Resilience, in the context of structural design, can be understood as the ability to reduce the chances failure, to reduce the consequences from failures (in terms of life safety, damage and negative economic and social consequences), and to quickly recover after a shock (Bruneau et al., 2006). Thus, resilience-based design (RBD) appears as a holistic process which identifies and mitigates earthquake-induced risks to enable rapid recovery in the aftermath of a major earthquake (Almufti & Willford., 2013). RBD exceeds code-intended performance objectives and typical performance-based design (PBD) objectives and requires integrated multi-disciplinary design and contingency planning together with performance-based assessment to ensure that an owner's resilience objectives are met.

One of the key differentiators of RBD is preparedness for post-earthquake recovery to ensure continued operation, if desired, and livable conditions immediately after the earthquake. This process considers the performance of the bridge and threats posed by the post-earthquake environment. Moreover, limiting damage significantly decreases the uncertainty in the behavior of the structure and increases the confidence that the bridge will perform as intended. RBD must explicitly incorporate the design and performance verification of the structure and all non-structural components, therefore both PBD and low damage design are key components of RBD.

Next to impacts on people, the physical infrastructure is often the most compelling “story” in the immediate aftermath of a disaster, as organized government services work to restore needed utilities and clear roadways of structural and other debris (Cimellaro et al., 2015). The public in seismically active, developed countries have a view that the level of technology which their country has should mean that structures can undergo a significant earthquake without damage. Consequently, is becoming more and more socially unacceptable that damage should occur to engineered structures in a significant earthquake.

The Yokohama National University made a trial in Japan interviewing the public about the desired performance goals in downtime and bridge performance from a public interview (Figure 1), where most on the people interviewed considered that the bridge should be able to be used immediately after an earthquake and that downtime should be within three days to a week.



**Figure 1. (a) Accepted downtime required by the public; (b) accepted seismic performance goals evaluated by the public (Yokohama National University, 2011)**

In a resilience context, performance levels (RPL) should be defined considering three dimensions: intensity of the event (IM), post-earthquake functionality (Q) and recovery time ( $T_{RE}$ ). (Cimellaro et al. (2015) proposed four RPL which recognize the importance of the temporal dimension on the functionality of the structures. The RPL combine different functionality levels with the recovery times (short, mid and long-term) forming a 2-D performance domain (Figure 2a). Then, by including the

effect of the IM of an event and the temporal dimension a 3-D performance matrix can be visualized as a set of predefined performance domains for different seismic IM and RPLs (Figure 2b).

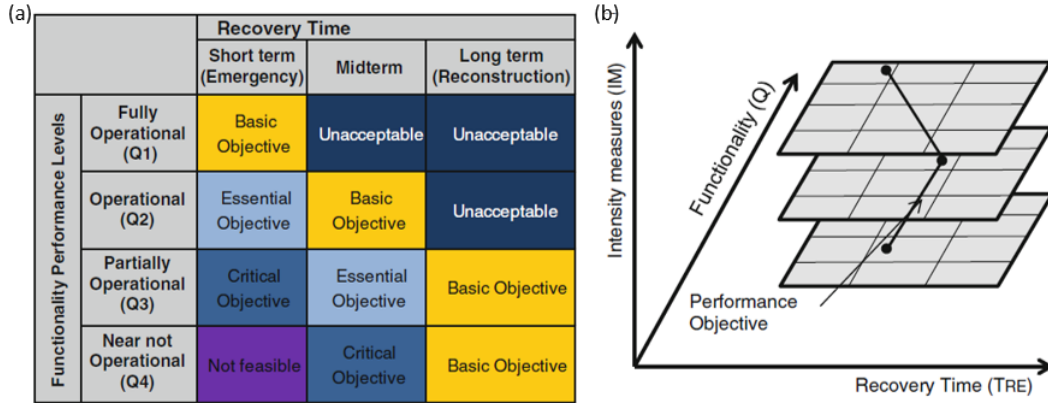


Figure 2. 3-dimensional resilience performance objectives matrix for structures (Cimellaro et al., 2015)

### 3 ENHANCED BRIDGE STRUCTURAL DESIGN

Research on the seismic design of RC bridges, has focused on improving performance in order to reduce physical damage and residual drift associated with plastic hinging. Developed damage-resistant technologies (DRT) intent to minimize post-earthquake damage in the bridge structure providing continued functionality for the transportation network. An example of a DRT is dissipative controlled rocking (DCR), also known as the PRESSS hybrid system (Priestley, 1996), which features a jointed connection that allows a structural member to rock, but, with the addition of unbounded post-tensioning (PT) for self-centering and dissipative devices across the rocking interface to add reparability, moment capacity and damping (Figure 3). In this design strategy, inelastic rotation, traditionally accommodated by member plastic hinging, is accommodated by rocking and gap opening at the base. This combination of PT and dissipation leads to a flag-type hysteresis as illustrated in Figure 4. The behaviour limits residual displacement after an earthquake provided the PT and axial load moment contribution (re-centering) is larger than the moment contribution of the mild steel.

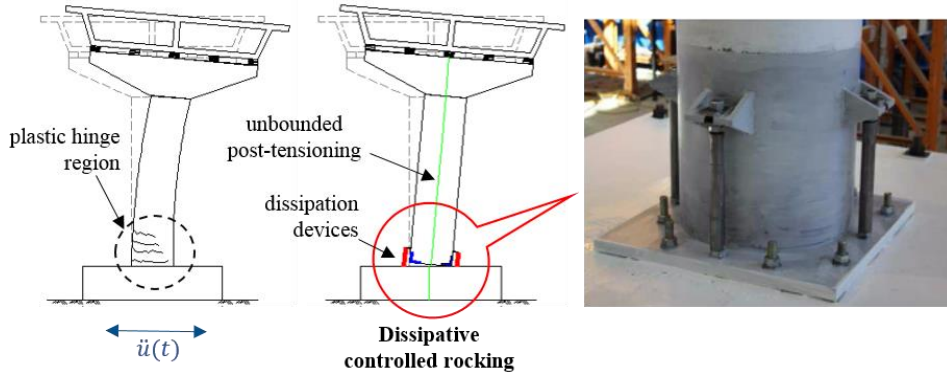
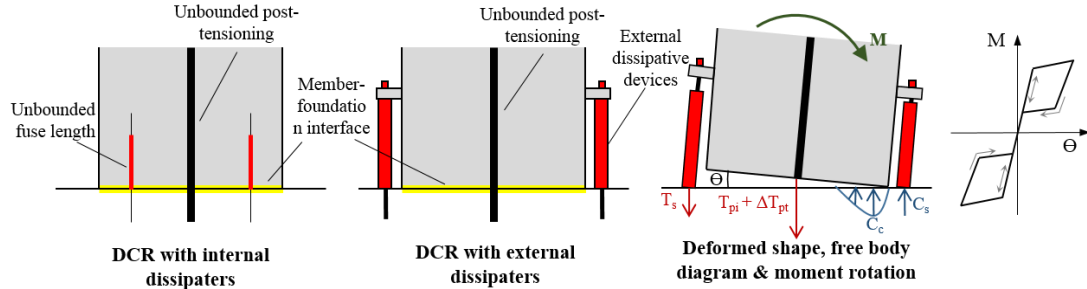


Figure 3. Example of a monolithic RC pier versus a DCR RC pier system.

The ideal thing about these connections is that after a design level event the connections can be repaired to 100% of the original capacity by replacing the external dissipaters (Marriott et al., 2009). The internal dissipaters represent a controlled damage connection, which is the more economical of the two solutions, and aims to localize damage to isolated areas of concrete and steel (Figure 4). The low damage connections aim to confine damage to the external dissipaters. For both connection types residual drift is minimized through the use of PT (Figure 4). The construction costs of low damage DCR connections is higher, however, it is quicker and cheaper to reinstate them post-earthquake.

Unlike plastic hinge design, low damage systems prevent residual drifts on the bridge due to its self-centering nature. Additionally, low damage technologies facilitate repair and inspection by incorporating replaceable dissipaters that can be unbolted and reinserted without any need for temporary supports or restraints. Since the extent of damage is significantly limited, no significant

cracking away from the main rocking interfaces is expected even after a collapse avoidance limit state and no significant spalling is expected at or near the rocking interfaces. Finally, control over damage lead to a minimized traffic disruption after an earthquake reducing indirect costs due to downtime all around the transportation network. The main drawback of low damage technologies is the novelty of the technology and slight increment of construction cost, which could be offset by the minimized traffic disruption and safer repair methods as well as the other advantages enlisted before. However, those benefits are not easily measurable nor are easily understood at a design level by owners and decision makers. This calls for new design approach that incorporates a repairing strategy and allow to develop recovery functions and resilience assessments for the bridges.



**Figure 4. Examples of DCR and concept including flag shaped hysteresis**

#### 4 IMPLEMENTATION – WIGRAM-MAGDALA CASE STUDY

The Wigram-Magdala Link Bridge (WMB) is located in Christchurch, New Zealand and connects Wigram Road and Magdala Place, linking the suburbs with the City Centre. The bridge consists of three spans of 32m, 35m and 32m length giving an overall length of approximately 99m (Figure 5a). The superstructure comprises simply supported 1525mm deep pre-stressed concrete Super Tee beams with a 200 mm thick in situ deck. The abutments consist of spill-through piled bank seats and the piers hold a headstock beam supported by two 1500 mm diameter columns (Routledge at al., 2016).



**Figure 5. Wigram-Magdala Link Bridge: a) Finished appearance of the bridge; b) match fitting base assembly; c) base plinth assembly; d) finished column on plinth**

Columns were designed to incorporate low-damage joints that comprise: circular steel-cased, concrete-filled columns on piled footings, replaceable dissipater volts connecting the stiffened column endplates to anchorages cast-into the footing and headstock and 75mm posttensioning bars across the joints. Hybrid joints located at and above ground level were proposed to ensure that the damage expected was minimal and any repairs required were simple to undertake. The ends of the column are



armoured with a steel plate casing providing high confinement to the concrete at the joint enabling increased concrete strains (Figure 5b). External grooved bar dissipaters are used (White & Palermo, 2016), the bottom ends of which are anchored by sockets cast into the footing and the top ends are anchored by nuts against slotted cleats welded to the outside of the casing (Figure 5d). These details provide easy access to inspect, remove and replace the dissipaters (Routledge et al., 2016). WMB is believed to be the first bridge in New Zealand, and possibly worldwide to adopt a low-damage ductile-jointed system.

When compared the performance and resilience of a DCR connection to a typical Monolithic Connection (MC), both connections are expected to have similar moment capacities; however, the DCR connection is to undergo larger displacements (Marriott et al., 2009), due to the additional damping of a traditional plastic hinge zone which reduces the demands in conjunction with the fact that yield displacement of the DCR connection is dependent on the un-bonded length of external dissipaters. It is important to note here that the design displacement is less important with these connections and can be altered by changing the geometry and the un-bonded length.

After a Damage Control Limit State (DCLS) event the performance of a MC connection becomes more uncertain as the concrete core can begin to degrade which can result in bar buckling and failure of reinforcement. This leads to a significant uncertainty with the cost of repair and the cost associated with downtime and traffic disruption. In addition, the structural scheme can also play a part in the repair costs and hence resilience. To illustrate the potential variation in repair costs and strategies the two monolithic bridges shown in Figure 6 are being examined. The bridges were damaged by the Kaikoura Earthquake, Mw 7.8, on November 14<sup>th</sup> 2016, and are situated approximately 2km apart and both span the Mason River. Both bridges, Lower Mason River Bridge (LMB) and the Rover Road Bridge (RRB), had similar structural systems and both exhibited plastic hinge zones (PHZ)'s with spalling of concrete, buckling of longitudinal reinforcement (Figure 7a) and in the case of the LMB fractured bars. Additionally, there was damage to the expansion joints, traffic barriers and water services (Figure 7b,c).



**Figure 6. PHZ damage after the recent Kaikoura Earthquake at the: a) Lower Mason Bridge; b) River Road Bridge.**



**Figure 7. Lower Mason River Bridge damage: a) bending of longitudinal reinforcement; b) failure of water pipes along the bridge; c) expansion joints and barriers.**

Repair of the LMB was carried out by Opus International Consultants and was relatively easy as the Mono-pile is larger than the pier so new reinforcement can be doweled into the existing pile and the pier re-cast, restoring the moment capacity of the column in about a month after the earthquake. In the

case of the RRB, repair will be very difficult due to the shape and size of the pier cap. This combination will make it quite complex to dowel in additional bars in and re-cast concrete. The result will be a significant repair cost and potential downtime for the structure.

DCR connections have much more reliable performance after the yielding of the steel dissipaters. This is due steel encased concrete which prevents concrete degradation at the interface. The dissipaters are the only component of the connection that require replacement, meaning that after any design level event be it DCLS or Collapse Avoidance Limit State (CALS) the replacement strategy is the same. This makes the connections particularly good when trying to develop a resilient network. Another advantage is that the reparability is the same regardless of whether the connection is designed for a design ductility of 4 or 6. This means the reduction in base shear demands on the structure will reduce the required moment capacity of the pier columns and hence reduce the over strength demands on other capacity-protected elements. The effect of this is that the increase in cost associated with this technology can be potentially offset by reducing demands elsewhere in the structure.

## 5 ROADMAP TO RESILIENCE

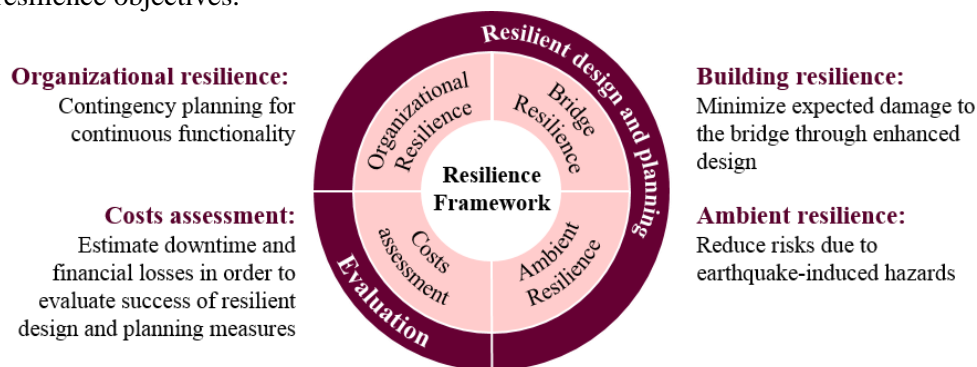
A framework, named REDi, for a RBD initiative for buildings was already proposed by Arup (Almufti & Willford, 2013). The framework, herein adapted to bridges, recognizes that resilient design and planning is the key to achieving a truly resilient structure. For a bridge to qualify as resilient it is necessary to satisfy mandatory criteria for each of three categories: organizational resilience, building resilience, and ambient resilience (Figure 8). In addition, evaluation through costs and downtime assessment must be performed to verify that resilience objectives are achieved.

### 5.1 Building Resilience:

Reliable damage-resistant technologies have become well established over the past 15 years, particularly dissipative controlled rocking (DCR), as mentioned on the previous section, has appeared as a method to significantly reduce damage to structures. Altogether, an improved knowledge of structural behavior, developments in analysis tools and computer simulation enable more realistic predictions of the behavior of bridges in large earthquakes. These advances make it possible to design economically viable structures which will suffer far less damage in strong earthquakes.

### 5.2 Organizational Resilience

Impeding factors can cause significant additional delays to recovery time, a resilient pre-earthquake contingency plan needs to be established so that risk drivers are identified and reduced in accordance with the resilience objectives.



**Figure 8. Resilience-based design framework for bridges**

### 5.3 Ambient Resilience

One lesson from recent earthquakes is that hazards external to the structure can impact recovery. In susceptible areas tsunamis, liquefaction, slope failures or other earthquake-induced hazards can have a devastating effect on the time it takes the network to recover. This could jeopardize the recovery of even the most structurally resilient bridges, therefore, earthquake-induced hazards which may require mitigation need to be identified and considered on the design according to the resilience objectives.

### 5.4 Costs Assessment

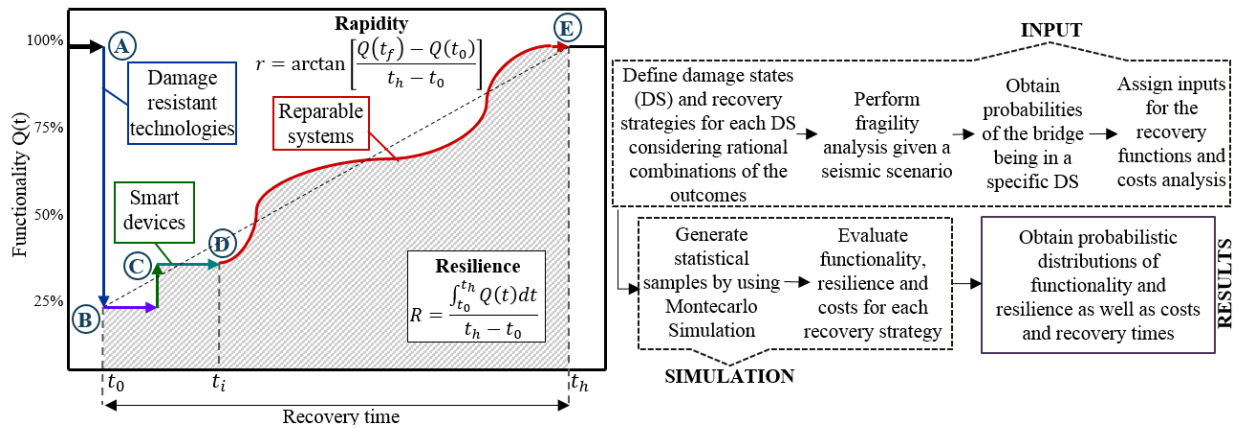
The losses induced by an earthquake are usually quantified by their associated monetary values. Direct and indirect costs and downtime can be used to measure the success of a resilience-based design

approach. Direct costs include those associated with the rehabilitation–reconstruction of the bridge, removal of debris, and the construction of a temporary bypass, while indirect costs are mainly caused by traffic disruption (Deco et al., 2013).

Ideally, for a structure to rank as fully resilient, enhance structural design of the structure and architectural components is required so that the damage is minimal and basically aesthetic. Mechanical and electrical equipment and other critical systems shall be protected, enabling continued operations of utilities, and in the event of an extended services disruption contingency plans need to be pre-identified. Risk of generally uncontrollable externalities which may affect the functionality need to be minimized, including site access restrictions and potential damage from external hazards.

Another mean of evaluating resilience is by integrating functionality of the bridge over time (Figure 9), from the moment when the earthquake happens, till the moment where functionality is fully restored. Currently, a probabilistic approach for the pre-event assessment of seismic resilience and recovery model for bridges have been proposed (Deco et al., 2013; Bocchini et al., 2012) and summarized on Figure 9, incorporating uncertainties associated with the expected damage, restoration process, and rebuilding and rehabilitation costs. As well, Figure 9 shows an idealized representation of functionality over time for a regular monolithical bridge with moderate damage after a major event. The functionality pattern is first determined by the pre-event level of functionality (point A), functionality suddenly drops when an earthquake occurs leading to a residual value (point B), which is conservatively estimated by a preliminary assessment and later on by the final bridge assessment, points C and D. Planning of rehabilitation works are represented by the flat horizontal segments. Finally, repair and rehabilitation works start (point D) leading to point E, this restoration process is calculated by using a recovery model. The information obtained by plotting functionality can be translated into resilience ratios, preliminary costs, repairability and time to regain full operability. Development of recovery functions for low damage will allow to compare the different DRT and to input repairability as a design parameter for concrete bridges.

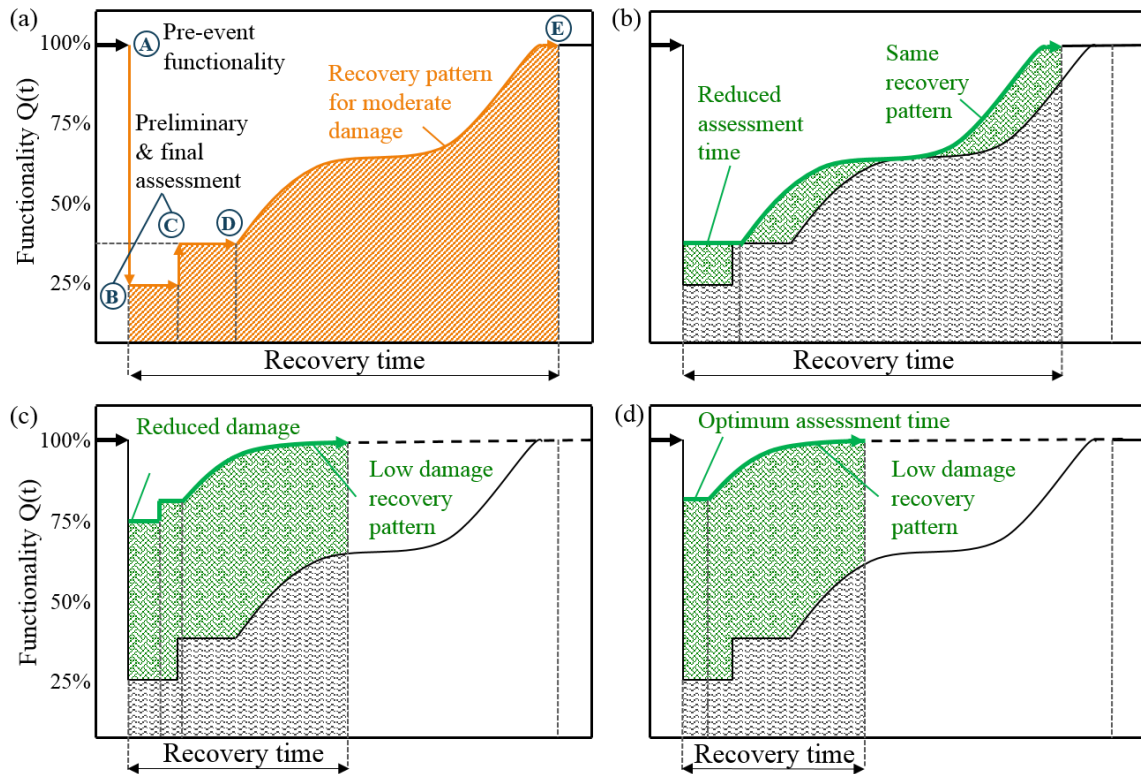
To improve resilience, the drop of functionality after the earthquake could be reduced by implementing damage-resistant technologies such as seismic isolation or DCR. Technologies that, additionally to energy dissipation, incorporate replaceable systems, as it is the case of low damage, will speed up both the planning of rehabilitation works and the repair process. Finally, implementing economical smart devices, such as health monitoring, that indicate the level of damage on the bridge, will facilitate the assessment after the earthquake.



**Figure 9. Schematic representation of resilience and rapidity and methodology for quantifying resilience.**

To exemplify this, Figure 10a shows the conceptual functionality curve for a traditional bridge presenting moderate damage after an earthquake. If health monitoring is incorporated on the bridge, for the same event, even if the recovery process would be the same the assessment time would be reduced (Figure 10b). With low damage connections no damage is expected to happen on the structural members, and the repairing strategy, replacing the devices, is well known by the designer accelerating the decision making and assessment after the earthquake (Figure 10c). In the case that, additionally to the low damage connections, smart devices are incorporated into the bridge, the recovery process will be even quicker and more cost-effective.





**Figure 10. Schematic representation of functionality over time for: (a) monolithic system; (b) monolithic system with health monitoring; (c) low damage designed; (d) low damage designed with health monitoring**

## 6 CONCLUSIONS

This paper has summarized the concepts of low damage design for concrete bridges and its advantages. Also, it showed as an example the case study of Wigram Magdala Link Bridge where low damage details have been used on a bridge for the first time. The bridge successfully incorporated low damage joints by adopting a DCR detail that comprises circular steel concrete-filled columns on piled footings, replaceable dissipater bolts connecting the stiffened column endplates to anchorages cast-into the footing and vertical unbounded post-tensioning across the joints. This project has demonstrated the ability to design and construct low damage details which are aesthetically appropriate for a bridge but also highlighted the need for design parameters that consider the benefits of DCR. These benefits were highlighted through the performance comparison between the MC and DCR case which highlighted that DCR connection were more predictable and robust.

Resilience-based design is the future of low-damage technologies since it introduces ways to incorporate reparability through the use of recovery functions and direct and indirect costs according to the post-earthquake functionality over time. Final aim of RBD is to make individual structures as resilient as possible allowing a full recovery of functionality as promptly as possible. In this paper, it was shown, at a conceptual level, the improvements on the functionality over time when low damage technologies or economical smart devices are implemented on the design process. With the proposed framework, it will be possible to translate the benefits of seismic mitigation technologies into concise meaningful terms such as expected closure time, recovery, direct and indirect costs and loss of functionality to all parts involved in a transportation project.

## 7 REFERENCES

- Almufti, I., & Willford, M. R. (2013). *Resilience-based earthquake design (REDi) rating system*, version 1.0. Arup.
- Bocchini, P., Decò, A., & Frangopol, D. (2012). Probabilistic functionality recovery model for resilience analysis. Paper presented at the Sixth International Conference on Bridge Maintenance, Safety and Management.
- Bruneau, M., Chang, S., Eguchi, R., Lee, g., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K.,



- Wallace, W., Winterfeldt, D. v. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, 19(4), 733-752.
- Chegini, Z., & Palermo, A. (2015). *Large-scale testing of low-damage superstructure connections in precast bridges*. Paper presented at the Tenth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Pacific.
- Cimellaro, G. P., Renschler, C., & Bruneau, M. (2015). Introduction to Resilience-Based Design (RBD). *Springer, Chapter 10*, 151-183.
- Decò, A., Bocchini, P., & Frangopol, D. M. (2013). A probabilistic approach for the prediction of seismic resilience of bridges. *Earthquake Engineering & Structural Dynamics*, 42(10), 1469-1487. doi: 10.1002/eqe.2282
- Marriott, D., Pampanin, S., & Palermo, A. (2009). Quasi-static and pseudo-dynamic testing of unbonded post-tensioned rocking bridge piers with external replaceable dissipaters. *Earthquake Engineering & Structural Dynamics*, 38(3), 331-354.
- Priestley, N., Calvi, G. M., & Seible, F. (1996). *Seismic design and retrofit of bridges*. USA: John Wiley & Sons.
- Routledge, P. J., Cowan, M. J., & Palermo, A. (2016). *Low-damage detailing for bridges – A case study of Wigram-Magdala Bridge*, (Mashal 2014), 1–8.
- White, S., & Palermo, A. (2016). Quasi-static Testing of Posttensioned Nonemulative Column-Footing Connections for Bridge Piers. *ASCE Journal*, 21(6).