WIGRAM-MAGDALA LINK BRIDGE – THE FIRST NEW ZEALAND BRIDGE WITH LOW-DAMAGE DUCTILE-JOINTED BRIDGE PIERS

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SUMMARY

In collaboration with the University of Canterbury (UC), Opus International Consultants has designed the first bridge in New Zealand (and possibly worldwide) to incorporate a low-damage ductile-jointed system – the Wigram-Magdala Link Bridge. This bridge showcases advancements in reinforced concrete technology, implementing recent UC research combining accelerated bridge construction and low-damage bridge detailing.

INTRODUCTION

The unusual constraints on the design of the Wigram-Magdala Link Bridge compelled Opus International Consultants to develop an innovative solution for the seismic resisting system. This created an opportunity to incorporate low-damage ductile-jointed connection details into the pier columns based on recent developments at the University of Canterbury (UC). Whilst low-damage details have become relatively common features on new buildings constructed in Christchurch in the aftermath of the recent Canterbury earthquake sequence, this project is the first to use low-damage connection details on a bridge in New Zealand and possibly worldwide.

Figure 1. Wigram-Magdala Link Bridge crossing over SH73 Curletts Road, in Christchurch
This paper will use the Wigram-Magdala Link Bridge (Figure 1) as a case-study to discuss the use of low damage-details on bridges. The paper will describe some of the unique constraints which led to the decision to adopt low-damage details on this particular bridge and will summarise some of the issues which needed to be overcome to incorporate the test prototype into a real bridge design. The paper will then discuss the opportunities and limitations which exist for future incorporation of low-damage details on bridge structures in general. In particular, the paper will discuss the potential for a shift in seismic design philosophy – The opportunity to permit controlled and easily repairable damage to occur in a lower return period earthquake than currently permitted. This will enable the more efficient use of materials, whilst still ensuring that collapse of the structure is reliably prevented.

BACKGROUND AND DESIGN CONSTRAINTS

The Wigram-Magdala Link Bridge is located in Christchurch, New Zealand and connects Wigram Road and Magdala Place, crossing over State Highway 73 Curletts Road. The bridge comprises three spans of prestressed concrete Super Tee beams with an overall length of approximately 99 m.

The pier foundations for this bridge were constructed in advance, as part of the adjacent Christchurch Southern Motorway Project, to minimise traffic disruption on Curletts Road. This resulted in an unusual situation whereby Opus was commissioned to design the bridge utilising existing foundations with constrained pier orientation, capacity and span arrangement.

The east abutment and pier has a 30 degree skew to accommodate the geometry of the underlying highway, while the west abutment and pier are square – adding to the design complexity – as shown in Figure 2.

Figure 2. Plan and Elevation of Wigram-Magdala Link Bridge showing site constraints and span lengths.

A change to the NZTA Bridge Manual (NZTA 2013) after the pier foundations were constructed resulted in the reclassification of Curletts Road to a Primary Lifeline Route (increasing Importance Level from IL2 to IL3), requiring the design seismic demands to be increased.
Primary Lifeline Routes have been categorised on the basis of volume of traffic carried, route strategic importance (e.g. interconnection of centres of population) and redundancy of the regional roading network. The reason for a higher design earthquake for structures on Primary Lifeline Routes is to provide a higher degree of security to the route to avoid significant disruption to these major roads. Since the bridge is crossing an Importance Level 3 road but carrying an Importance Level 2 road, the argument was made that the design level earthquake could be relaxed to Importance Level 2 provided collapse in a major event was prevented and provided any damage would not affect the function of Curletts Road below, even if the bridge itself had reduced functionality after an earthquake. Furthermore, repairs to restore the bridge to an acceptable long term level required minimal disruption to Curletts Road.

These unusual constraints on the design compelled Opus to develop an innovative solution for the seismic resisting system of this bridge. As a result of extensive interaction with UC through the Canterbury Bridge Group, Opus identified an opportunity to use a low-damage column connection detail for the new Wigram-Magdala Link Bridge based on the UC prototype. These hybrid joints located at and above ground level were proposed for use in the columns to ensure that the damage expected was minimal and any repairs required were simple to undertake. To demonstrate that the design had not compromised on the level of protection against collapse, the major earthquake considered appropriate for the Collapse Avoidance Limit State (CALS) was the same as that for an Importance Level 3 structure even though the Damage Control Limit State (DCLS) design level was taken as that for an Importance Level 2 structure.

Christchurch City Council was supportive of the innovation for this structure, NZTA accepted the reduced design level earthquake in this circumstance and the University of Canterbury assisted Opus International Consultants with conceptual design inputs and peer review of detailed design of the low damage details.

LOW DAMAGE DETAILING

Low damage bridge pier detailing had been observed in scale model testing in the UC laboratory, and was an attractive option for use in the Wigram-Magdala Link Bridge design to overcome the unique constraints of the site.

This type of low damage technology has become known as Dissipative Controlled Rocking (DCR) technology, to acknowledge the following key features:

- **Dissipative** – Yielding occurs in the external dissipaters.
- **Controlled** – Damage is concentrated in the dissipaters, which are designed to yield and damage is minimal in other areas due to armouring of the rocking interfaces. Dissipaters are designed to be easily accessed and replaceable after damage.
- **Rocking** – Self centring behaviour is provided by the axial post-tensioning, resulting in minimal residual displacements.

Low damage technology for reinforced concrete bridges is a further development stemming from hybrid PRESSS technology for concrete buildings to control damage in plastic hinge regions. Guidance for the design of these systems is provided in NZS 3101 Appendix B (NZS 2006) and the PRESSS Design Handbook (Pampanin et al. 2010). A number of new buildings in Christchurch have utilised these technologies.

The University of Canterbury (UC) has been further developing this technology as part of the government funded project “Advanced Bridge Construction and Design”. One development from this project was a prototype precast low-damage connection (Mashal and Palermo 2014) for bridge bents which is a further refinement of previous research carried out by Mariott et al. (2009).
The low damage DCR detailing tested as part of the UC research consisted of an armoured precast column with internal axial post-tensioning and external grooved bar dissipaters (White and Palermo 2016) anchored into the footing and to the armoured casing. Steel tubing over the length of the dissipaters provides buckling restraint. Externally located dissipaters are easy to access for inspection, removal and replacement after damage.

Whilst the low-damage details used in the Wigram-Magdala Link Bridge design were based on a prototype tested at the University of Canterbury, they required modifications for aesthetic reasons to be acceptable to CCC. This prompted the development of a buried version of the joint enabling the dissipaters to be hidden within the concrete footing but detailed in such a way as to ensure the dissipaters are readily replaceable. Several innovations were made to overcome the numerous challenges presented by this buried joint concept (Routledge et al. 2016).

The primary considerations which needed to be addressed, particularly those arising due to the decision to bury the low-damage details are:

- Ease of replacing the dissipaters and post-tensioning
- Durability of the dissipaters, post-tensioning, shear keys and hidden steel interfaces
- Buckling restraint to the dissipaters
- The availability and size limitations of a suitable seismic steel grade for fabricating the dissipaters
- Avoidance of thread damage (as this would hinder dissipater removal in a buried detail)
- Increased efficiency of the dissipaters (compared to the UC prototype) due to their increased effective depth as a result of stiffened column base plates

Figure 3. Elevation and section on typical pier showing low-damage details (top left), and enlarged view of low-damage connection to pier footing (bottom right)
The final design of the bridge successfully incorporated low-damage joints, enabling easy replacement of the ductile elements that would be damaged during a major earthquake. This was achieved by adopting a DCR joint detail which in this case comprises (Figure 3):

- circular steel-cased, concrete-filled columns on piled footings
- replaceable dissipater bolts connecting the stiffened column endplates to anchorages cast-into the footing and headstock (Figure 4 and Figure 5)
- vertical unbonded post-tensioning across the joints

Figure 4. Prefabricated dissipater sleeves and shear keys – a) in the shop (left); b) fixing in the columns plinths (centre); and c) in completed column plinth (right)

Figure 5. a) Installing dissipaters into plinths (left); b) Prefabricated columns showing baseplate (centre); c) Finished column on plinth (right)

The cost of this steel column with low-damage details was higher than that of conventional reinforced concrete columns. However, the specific constraints on the design of the Wigram-Magdala Bridge created a favourable opportunity to explore this detail regardless of the higher cost.

The experience gained from the design and construction of a full scale bridge with low-damage detailing has been invaluable to inform and direct future research at the University of Canterbury to further develop and refine the DCR connection.

Key points for further investigation to develop a more efficient connection configuration include:

- The dissipaters require a necked down or grooved portion where the damage is concentrated to prevent yielding in the threaded ends. Current recommendations require a large portion of the steel cross-section to be removed in the fabrication process, so further refinement of this recommendation would lead to a more efficient design.
- Confirming a reliable supply of large diameter bar/rod with known characteristics for fabrication of dissipaters with dependable ductility.
A NEW MORE EFFICIENT SEISMIC DESIGN PHILOSOPHY

The challenge of designing Wigram-Magdala Link Bridge to cross an IL3 highway whilst making use of the existing foundations (designed to IL2) resulted in the use of an alternative seismic design philosophy. The inherent resilience of low damage details was innovatively used to successfully overcome this design constraint without a negative impact on the IL3 highway.

A resilient transport network has minimal reduction in levels of service following an adverse event, such as an earthquake, and enables quick recovery of service levels as shown in Figure 6 (Brabhaharan 2006). Seismic resilience in Bridge design within New Zealand is currently rather crudely considered based on the Importance Level determined for a particular bridge structure. The importance level is defined in the NZTA Bridge Manual (NZTA 2016a) based on the potential loss of human life and the economic, social and environmental consequences of failure of the bridge. The Importance Level is then used to define the return period for Serviceability Limit State (SLS), Ultimate Limit State (ULS) and the Maximum Credible Earthquake (MCE). These limit states have recently been more appropriately renamed, for seismic design, in the latest version of the draft NZTA Bridge Manual (NZTA 2016b) and other international displacement-based seismic design provisions, as Serviceability Limit State (SLS), Damage Control Limit State (DCLS) and Collapse Avoidance Limit State (CALS) respectively. These new terms help clarify that what used to be termed Ultimate Limit State is not in fact about life safety but rather about controlling damage and it is the CALS that is about ensuring life safety.

![Figure 6. Resilience of a Transportation Network](image)

In conventional forced-based seismic design, the displacement ductility factor ($\mu$) provides a means by which, a structure can be designed for lower seismic loads on the basis of accepting more damage in a particular DCLS event. For this reason, the NZTA Bridge Manual places a limit on the acceptable displacement ductility factor. This is dependent on the location of a plastic hinge (e.g. >2m below ground, above ground etc.) which strongly influences the ease of access for inspection and repair. Aside from this, there has not traditionally been a specific focus on maximising resilience and, in particular, about maximising the speed of repair following an earthquake.

The alternative seismic design philosophy is based on the premise that as long as the appropriate CALS (which ensures life safety) is satisfied for a particular Importance Level structure, it would be justifiable to define alternative appropriate SLS and DCLS return periods based on the economic and social impacts of the expected damage and speed of repair.
In order to utilise the existing foundations, Opus justified the use of a smaller design earthquake (IL2), provided that life safety was not compromised and any damage/repairs would not significantly affect the serviceability of Curletts Road. To demonstrate that life safety has not been compromised in this case, the major earthquake considered for Collapse Avoidance Limit State (CALS) was selected assuming an IL3 structure, while the design earthquake considered for the Damage Control Limit State (DCLS) was reduced to that for an IL2 structure.

A key outcome from this project is that this alternative design philosophy could be applied more generally to all bridges that use resilient low-damage DCR detailing. Reduced design level (DCLS) demands result in more efficient use of materials, due to the reduction in base shear demand which in turn reduces the necessary capacity of ductile elements and overstrength demands on capacity protected elements. Structures which have been specifically designed for controlled low damage and easy repair can be justifiably designed to a lower DCLS return period provided there is no compromise on life safety.

The ‘catch’ is that the displacement demand is inversely related to the stiffness of the seismic resisting system. Hence, weaker pier columns reduce the stiffness and increase the displacement demand. Therefore, the ‘penalty’ for this economy in design is the need to achieve relatively higher displacements (including allowing for p-delta effects and seismic gaps etc.) at the CALS than would have been required had a more onerous DCLS been used.

Figure 7. Comparison of Conventional and More Efficient Seismic Design Philosophy

The diagram illustrates this principle. Say a bridge was classified as an Importance Level 3 structure and designed using a low damage (DCR) detail but as currently required using a conventional design philosophy with a DCLS return period of 1/2500 years. This would imply that there is in the order of a 4% chance that the bridge may experience a damaging earthquake (requiring repair) within its 100 year design life. However, since a low damage (DCR) connection detail was to be adopted, the client may be prepared to accept a higher risk of damage (and repair) within the life of the bridge on the basis that the reduction in service as
A result of the damage is minimal and the bridge can be repaired quickly due to the benefits of the low damage detailing.

An alternative approach using a more frequent return period of 1/1000 years as the DCLS (typical for an IL2 structure) leads to a more efficient design philosophy. This would imply a 10% chance that the connections will be damaged within the bridge design life. If the connection capacity was reduced to this level of demand, then to provide the same level of robustness (i.e. to satisfy the CALS at IL3) the corresponding CALS drift demand would need to be accommodated. The relative performance of the two theoretical design examples is illustrated in Figure 7, where the more efficient design philosophy satisfies IL3 CALS but with a reduced DCLS return period of 1/1000 years (equivalent to IL2). The conventional design example also satisfies IL3 but using the normally specified DCLS return period of 1/2500.

It is apparent from the figure that the conventional design philosophy has significantly more displacement capacity available than the IL3 CALS demand for this connection and hence DCLS is governing the design. It is also apparent that there is significantly more displacement capacity available than the IL2 CALS demand in the case of the more efficient design philosophy, allowing the design to just satisfy its corresponding IL3 CALS demand. Therefore, the more efficient design philosophy essentially meets the life safety requirements for an IL3 structure but better utilises the materials to enable CALS to more appropriately govern the design.

Figure 8 compares the force/displacement capacity performance of a typical monolithic reinforced concrete connection and an equivalent low damage connection. Whilst the low damage connection has higher displacement capacity, a well-detailed monolithic pier is also able to undergo large displacement demands before collapse and it may be possible to allow CALS to govern the monolithic pier design. However, such an approach has traditionally been avoided due to difficulties in reliably predicting behaviour close to collapse and instead it has been conventional to design to satisfy DCLS. CALS is then deemed to comply on the basis that there is sufficient margin of safety beyond DCLS to avoid collapse in a larger earthquake.

![Figure 8. Force/displacement comparison of DCR (low damage) with monolithic connections](image)

The use of displacement-based design and the minimal degradation of low damage joints makes performance at CALS more reliable. To illustrate this, compare the photos in Figure 9 which shows a low damage joint and a conventional monolithic column each at approximately CALS drifts. There is little apparent damage to the low damage joint whereas the monolithic plastic hinge has experienced significant spalling, buckled and fractured bars, reduced shear.
capacity and permanent deformation of the column making behaviour at this level of displacement unreliable. At the CALS drift the dissipaters in the low damage connection are also beginning to rupture. However, high confinement to the concrete, the positive shear connections and the fact that 60% of the moment capacity is typically provided by post-tensioning and axial load, means that there is significant and reliable residual capacity in the connection even after dissipaters have ruptured. This provides a further margin of safety against collapse. Understanding the performance and margin of safety beyond dissipater fracture will provide more confidence in allowing CALS to govern the design in these low damage connections. This conceptual behaviour has been verified through non-linear time history analysis by McHaffie et al. (2017).

Figure 9. Low damage connection (left) and monolithic connection (right) at CALS drift

Another reason why the application of this philosophy may not be appropriate for monolithic columns is that having a more frequent return period means that damage will occur at lower levels of shaking. This can be justifiably accepted for low damage connections as these structures can be quickly and easily repaired whereas for monolithic structures it will be less acceptable due to the downtime and cost of repair.

University research by Sarkis and Palermo (2017) exploring the concept of resilience based design for bridges has recently been undertaken using the DCR detailing on Wigram Magdala Link Bridge as a case study. A more efficient seismic design philosophy which adopts a lower seismic design level provides an ideal and more economical way of utilising low damage technology to achieve resilience based design.

CONCLUSION

Wigram-Magdala Link Bridge showcases low damage details used for the first time in New Zealand in reinforced concrete bridge piers. This project has demonstrated the ability to design and construct low damage details which are aesthetically appropriate for a full scale bridge. It has also highlighted some key issues which need to be worked through when considering the future use of low damage details.

This paper has presented a possible alternative seismic design philosophy to justify design at the Damage Control Limit State for a smaller (albeit increased likelihood) earthquake. This is justified by taking advantage of the unique benefits low damage details, namely the limited damage and, reliable and resilient behaviour post-damage which ensures minimal reduction in service and quick repair following an earthquake.
Future research to develop and refine the DCR connection details will make this technology an attractive solution for new bridge design. In addition to this, more guidance is needed on the appropriate application of this technology for different bridge forms and foundation types. Further guidance on this alternative design approach is also recommended to inform asset owners and designers on how they may benefit from and apply this technology.

In the short term the economies in design and construction as a direct result of smaller design earthquakes can be used to offset the higher upfront costs of the low damage connection details. In the long term it is expected that, as these low damage connection details become more common, the cost of design and construction will reduce. The combined effect of a lower design level earthquake and the other whole of life benefits of low-damage details will lead to more economic bridge designs, which are more resilient to larger earthquakes; easier, safer and less costly to repair; with reduced risk of disruption to traffic networks following major earthquakes. Paradoxically, designing bridges with low damage details for a smaller earthquake will ultimately lead to a more resilient road network at lower cost.

REFERENCES


