ACCELERATED BRIDGE CONSTRUCTION (ABC) IN EARTHQUAKE PRONE AREAS, INTERNATIONAL TRENDS AND NEW ZEALAND NEEDS

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ABSTRACT

During recent earthquakes in New Zealand, bridges didn’t collapse however, some critical arterial routes lost their functionality. Life Safety is still our primary objective but nowadays we are moving towards new society’s targets which aim to limit at minimum business disruption as well. Preserving the functionality of a bridge structure after a MCE (Maximum Credible Earthquake) event is the further objective that research community will be targeting in the next 20-30 years. In order to save the economy and life of the people, it is vital that bridges remain drivable after a natural disaster, such as an earthquake.

More importantly asset managers/networks’ owners want rapid response, flexibility, efficiently from contractors/designer with limited budgets. Therefore in very populated urban centres or a critical network location an Accelerated Bridge Construction (ABC) technology with durable materials and low-damage technology is envisaged.

American Association of State Highway Transportation Officials (AASHTO) started in 2002 a long-term strategic bridge plan which aims to cover all these issues. Japan started before similar research strategy, Europe is slowly going towards ABC. What is New Zealand vision for the next 20-30 years?

This paper aims to give an overview of the current international trends and challenges, focusing on new innovative ideas in bridge engineering and contextualizing them in a possible New Zealand background.
INTRODUCTION

Many bridge structures in New Zealand are aging, the activities concerned with the maintenance, retrofitting and frequent inspection of these bridges can cause severe traffic congestion and disruption. We are expecting to extend the serviceability life of a bridge structure to 100 years with the intent to minimize maintenance costs.

More importantly, during bridge life natural hazards like earthquakes might have tremendous impacts on post-earthquake repairing strategies and therefore on the whole network. A clear example is the Canterbury earthquake which imparted important lessons [1]. In fact, despite bridges didn't collapse and performed structurally well, some critical ones lost their functionality causing traffic disruption to the city.

We are moving towards new society’s targets which imply to limit the business disruption to its minimum. Preserving the functionality of a bridge structure after a MCE (Maximum Credible Earthquake) event is the further objective that research community is targeting [2]. In order to save the economy and life of people, it is vital that bridges remain drivable after a natural disaster. Furthermore, the public community will feel safer and less vulnerable if the bridges preserve their integrity after a seismic event. A bridge is an important and visible part of a country’s infrastructure.

The efforts for post-earthquake recovery of damaged bridges have caused too much traffic interruption to such an extent that communities cannot reliably plan their travel timing. Nowadays, the basic demand of communities is durable and earthquake resilient infrastructures, which should be strong enough to sustain extreme loadings without experiencing any structural damage or loss of functionality. At the same time asset manager/network owners want quick response, flexibility, efficiency from the contractors/designer with limited budgets. In a very populated urban centre or critical network location an Accelerated Bridge Construction which also carries features like long-term resilience is really envisaged. The Accelerated construction techniques, high performance durable materials combined with advanced earthquake technology are the success recipe of the next generation of bridges.

The research community has always been aware of the above mentioned challenges. The researchers in the United States have come with very cost-effective and practical solutions, such as the American Association of State Highway Transportation Officials (AASHTO) Strategic Bridge Plan, started in 2005 to improve the behaviour and response of the bridge structures [3]. One of the proposed solutions is having more coordination and involvement of the research community with the Departments of Transportation (DOTs), contractors, and designers, which is necessary to achieve the goals for durable, cost-effective during construction and more importantly low-damage earthquake resistant bridge structures.

Is New Zealand Bridge Community going towards ABC? To achieve this, all other parties, such as New Zealand Transportation Agency (NZTA), Kiwi Rail, key city councils (Auckland, Wellington, and Christchurch), contractors, practitioners and more importantly, the researchers should synergistically cooperate with a long term vision and strategy.

This paper aims to give an overview of the current international trends and challenges, focusing on new innovative ideas in bridge engineering and contextualizing them into typical New Zealand functional requirements.

WHY ACCELERATED BRIDGE (ABC) CONSTRUCTION IN SEISMIC REGIONS?

Cast-in-place substructures for bridges are the most commonly used technology regardless of the bridge dimensions (span lengths, pier heights). The use of cast-in-place formwork for standard column shapes (circular or rectangular) is very cost effective. The precasting of bridge components in the past has been intended primarily for superstructure elements for bridges with short and moderate spans. These bridges support girders of I, T, U, and box sections. However, construction time, and un-skilled labour can drastically impact on construction timeframe, causing further disruption and alteration to the business and the asset management of clients respectively.
Therefore, in the past 20 years, a total prefabrication of bridges (substructure and superstructure) has been promoted especially by the DOTs in the U.S. [4]. A clear example is the Texas Department of Transportation which has been promoting the use of prefabricated bridge element for years. The reason behind has been to reduce the impact of bridge construction on the traffic, especially in busy urban places. A higher speed of construction is not only the main reason, in fact if the elements are prefabricated in a factory then the material and tolerances quality control are certainly higher and therefore life cycle costs will be reduced.

There are plenty of examples for precast pier caps such as the Pierce Elevated Freeway Bridge Replacement project, and the Louetta Road Overpass [5]. The columns were precast segmentally and took short time to assemble them on site. Other examples of precast concrete piers are Seven Mile Bridge, Sunshine Skyway Bridge, Vaina-Enon Bridge, John T. Collinson Rail Bridge, Linn Cove Viaduct and just recently, Victory Bridge in state of New Jersey, “Vail Pass” in Colorado, and the Texas State Highway 183 in Austin, Texas (Figure 1).

![Figure 1: Precast Segmental Piers of the Vail Pass in Colorado (left-middle); Texas State Highway 183, Austin, Texas (right)](image)

The latest construction technology for the precast segmental box construction has been tremendously evolving and recent contributions presented by Billington [6] focuses on standardization of the precast segmental substructure system as shown in Figure 2.

![Figure 2: Precast Segmental Pier Supporting Individual Pre-tensioned U-Beam (left); elements of Precast Segmental Pier (middle-right), after [6]](image)

ABC advantages can be summarised as follow:

- Limited disruption in traffic while construction work is in progress, especially in populated areas
- Fast project delivery
• Saving cost for formwork
• More accuracy in bridge elements as they are prefabricated
• Better quality control of material used in bridge elements
• Lowering the cost of machinery and equipment
• Higher durability
• Reducing the total weight of bridge structure
• Reducing the safety related issues as well as minimizing environmental impacts

Although ABC for bridge piers is becoming more popular in regions with low seismicity, high criticism and lack of confidence still appears if the technology applies in the earthquake prone areas. The earthquakes happened in 70 and 80s [7] highlighted unexpected higher vulnerability of the precast concrete structures in general. This caused further evolvement of the Standards which penalised through more conservative reduction/ductility factors for precast concrete structures [8].

For buildings, the structural designers accepted the compromise to have partially prefabricated elements combined with the cast-in-place joints, intending to emulate the real cast-in-place technology. This certainly has the advantage of achieving the same ductility as for a cast-in-place structure, but at the same time it is detrimental for the speed of construction.

Nowadays civil engineering technologies are evolving; even though compared to the other disciplines, the growth is slower we should be going towards a "mechanized system" which allocates most of the seismic demands in high-tech linkages/devices. In this way we would be able to not only compromise the construction time (less labour cost) but also to limit damage to the structural members, i.e. no formation of plastic hinges in the members.

We believe that our society will slowly abandon the concept of the emulative cast-in-place technology and will migrate towards ABC with damage free concepts, “Advanced Bridge Construction and Design” (ABCD).

However, in order to achieve this goal, some special design/detailing specifications and criteria are required for a proper implementation of ABC with advanced technology. Being in the 21st century and seeing examples of the magnificent engineering successes built 2000 years ago such as Roman aqueducts, we believe that our current engineering society should be able to face this challenge, and find the appropriate solutions.

INTERNATIONAL TRENDS

United States of America, Japan, European countries interpreted and developed Accelerated Bridge Construction based on different ways. This is due to fact that different society needs lead towards different evolvement of their technologies. A summary of the overseas activities is reported in the following paragraphs.

United States

United States is composed of over 46,500 miles (74,800 km) of roadway. Following the rapid advancement of the transportation network in the second half of the twentieth century, the technology for innovative ideas of seismic-proof bridge design and construction is been changing its shape.

The California Department of Transportation (Caltrans) and AASHTO have a broad picture for improvement of ABC in their strategic plan. Caltrans already included ABC as an element of Accelerated Project Delivery (APD), which has many benefits such as leading to expedited capital improvement, and improving the state’s economy. The NCHRP 20-73, Accelerating Transportation Programme and Project Delivery: Conception to Completion, is one of the recently accomplished projects in the U.S., [9]. At National level, there have been numerous workshops and report on ABC recently such as:

- 2006 ABC Workshop, Reno, Nevada
In a first phase of the strategic research plan [10], Caltrans aims to focus on connections. In particular, research will be carried out on grouted splice sleeve connections (Figure 3), precast concrete or steel girder to integral cap joints using extended reinforcement, precast pile extension to precast bent cap connections. The second will focus on structural systems.

![Edison bridge, Florida: fully prefabricated structure with grouted splice sleeve connections](image1)

**Figure 3: Edison bridge, Florida: fully prefabricated structure with grouted splice sleeve connections**

In the same time, there were a number of bridges which were replaced with ABC in California. As an example the I-40 Marble Wash Bridge was replaced by precast girders, and was completed only in 28 days (Figure 4).

![Replacement of I-40 Marble Wash Bridge with precast girders](image2)

**Figure 4: Replacement of I-40 Marble Wash Bridge with precast girders, (Caltrans, 2008) (left, middle left); precast bent cap in Conway Bypass (right) [11]**

In last three years all ABC projects in California were completed in less than 5 months. Caltrans is currently sponsoring workshops with consulting engineers, fabricators, erectors, trucking, and general contractors in order to engage the industries to improve construction cost and quality of new precast components and details solutions, [10]. There are a number of ABC candidate bridges in the USA. The 1605/I10 Interchange Viaduct on San Bernardino Freeway in California with a total length of 1Km, 16-spans (64-82m) and height of 9.1m is the next ABC project candidate.

**Europe**

European trends for ABC don’t comprise any innovative or accelerated construction technology for bridges substructure in seismic areas. However, seismic isolation of bridges, i.e. low damage technology is growing exponentially and huge efforts have been put in order to make those solutions cost competitive with traditional cast in place solution. However, different varieties of ABC decking systems are currently in use. The most common is the steel-composite deck with precast concrete panels (partial or full precast)
connected through studs to the steel beam (Figure 5, left). Reduced time of construction and weight are the key reasons for the spreading of the technology.

**Japan**

Japan presents similar trends to Europe especially for ABC decking technology. After the 1995 Kobe earthquake, use of post-tensioning has been strongly envisaged as an effective way to reduce permanent post-earthquake drifts/displacements. However, ABC bridge piers are not very popular. Only recently, Sumitomo Mitsui Construction Company developed a rapid construction system (SPER) which allows to reduce construction time of 60-70% respect to cast in place technology. SPER consists of prefabricated panels with pre-inserted cross ties. Each segment is stuck on top of each other and fixed through epoxy joints. Concrete is then successively cast inside in order to form a solid section. Those high performance concrete panels act as a sort of structural "shell" for the bridge pier and replace the formwork. Similar concept is under development in U.S. at University at Buffalo [13] adopting a steel tube as structural shell instead of precast concrete panels.

![Figure 5: Prefabricated Composite Deck (left); SPER bridge technology [12]](image)

**NEW ZEALAND CURRENT PRACTICE**

Currently the state highway network in NZ includes about 11,000 kilometers of roads, more than 4000 bridges and large number of culverts. The combined length of bridges on the state highway network is over 140 kilometers. Reinforced concrete bridges and culverts cover approximately more than 80% of the combined length and almost 75% of bridges. Precast concrete is half of the production of cast-in-place but it's quickly taking over, since most of the old existing R.C. bridges were built in the 50s and after terminating their service life, they are generally replaced with the precast concrete decking system.

![Figure 6: Summary of Beam Types Produced, after [14]](image)

In New Zealand, bridges with small span length (15-30 m) are typically constructed with precast decking, which can be either continuous or simply supported with cast-in-place sub-structure (piers and foundations). An R.C. solution (cantilevered construction, launched, etc.) is envisaged for bridges with more than 30m spans as part of functional requirements. Therefore we can certainly argue that, for small-span bridges the construction is partially accelerated (only limited to deck). However, it’s important to
mention that in most cases the heights of the piers are reasonably low (up to 5-6 m). Therefore, this justifies the choice of adopting cast-in-place technology, since construction time should not be excessively long. Figure 6 (left-middle) shows an example of typical bridges with precast bridge decking and cast-in-place piers. Bridge girders with I-sections are still the most popular (Figure 6 right) for moderate spans while duo-hollow core units is very efficient and cost effective if small spans are targeted, (refer to Figure 7). However based on the recent NZTA research report [15], this trend might change in future.

![Diagram of bridge types](image)

**Figure 7:** Summary of Beam Types Produced, after [15]

From the seismic design prospective, having the bridge substructure as the sacrificial part of the structure under earthquake loading, the practitioners in NZ feel confident to adopt this cast-in-place piers which accommodate the formation of plastic hinges in their critical zones. The Northridge earthquake [7] imparted several lessons for precast concrete decking; therefore the practitioners’ perception is that the more cast-in-place or emulation of cast-in-place is incorporated in the bridge the better the performance of the structure will be. NZTA Bridge Manual [16] indirectly drives the bridge practitioners towards cast-in-place solution. In fact, it gives details on design with plastic hinges in bridge piers (Figure 8), but briefly mentions advanced solutions (sections 5.5.8 for rocking foundation structures and section 5.5.9 for bridges adopting dissipative devices) which could be combined quite well with ABC.

![Diagram of plastic hinges](image)

**Figure 8:** Location of Plastic Hinges and Related Global Displacement Ductility Factor [16].

**VISION FOR THE NEXT GENERATION OF NEW ZEALAND BRIDGES: BACK TO THE PAST**

New Zealand has always been on the roof of the world for pioneering the design concepts in earthquake engineering. Capacity design principles introduced by T. Paulay and B. Park have been a revolutionary step in earthquake design, which immediately and beneficially impacted the New Zealand bridge
engineering standards, construction and design. Despite living a flourishing past, in the last 10 to 15 years, the research in bridge engineering field has significantly decreased, as also mentioned by Kotze, [17]. Technologies evolve based on society’s needs and countries like the U.S. and others are already visioning this. Unfortunately, they don’t wait for us and we can’t be living on the legacy of the past for too long.

The Sport activity is very similar to Research and Practice. In fact, a top-world marathon athlete needs constant training to keep him at the top of the ranking and win competitions. Research is like the “training” for the engineering community, with researchers as the training coaches, and the practitioners as their athletes. Let’s start winning again within the next 20-30 years!

Luckily we can start from a solid background; the next paragraphs give a brief overview on the past and recent research work in overseas and New Zealand for the next generation of bridges.

Pioneers of advanced seismic bridge engineering technology

In the 70 and 80s, New Zealand already featured advanced seismic engineering technologies which incorporated concepts of dissipative connections/devices to absorb kinematic energy induced by earthquakes. The idea of using mechanical devices becoming the weakest link of the capacity structural chain can be considered as a precursor for the next generation of structures and specifically for bridges. One of the pioneers is certainly Bill Robinson who invented the lead extrusion energy absorber in 1976, and after the occurrence of earthquakes in USA (Northridge 1994) and Japan (Kobe 1995), its use had tremendously increased. Another person who certainly contributed in this field is Ivan Skinner. His contributions were not only limited to the development of innovative “cheap” advanced devices/isolators but also to the implementation of these technologies into structural design [18]. As an example, the South Rangitikei viaduct spanning over the Rangitikei River, the 4th highest railway viaduct in New Zealand, opened in 1981, (also the 2nd longest viaduct in New Zealand), 78 m high, 315 m long. It is an impressive all-concrete structure with twin-shafted vertical piers carrying a continuous prestressed hollow box superstructure of six spans. The viaduct is an example of isolation through controlled base-uplift in a transverse rocking action. When an earthquake occurs, the pier bases could lift up to 13 cm to allow energy and pressure to shift from one pier leg to the other. The rocking action is controlled by large "energy dissipaters" installed in the pier bases. Figures 9 (left and middle-left) show the schematic of the stepping isolation system while Fig. 9 (left) illustrates the steel torsional damper with transverse loading arms.

Figure 9: Stepping Rail Bridge over Rangitikei River in New Zealand (left); schematic for the base of stepping pier (down-middle); picture of the base of stepping pier (top-middle); steel torsional-beam “Type E” damper (right), [18].

Seismic isolation or dissipative devices developed in the 70s, 80s are still greatly used in the current overseas bridge practice but not to such an extent in New Zealand. These technologies can be used in a good conjunction with ABC, minimizing the traffic disruption during construction and post-earthquake repair works.
Literature review on ABC with low Damage technologies

Damage free solutions for ABC’s in high seismicity areas work mostly relying on rocking motion of the substructure on the foundation system. Traditional post-tensioning techniques, i.e. unbonded strands/tendons or high strength steel bars, which are used to clamp precast elements of the pier provide self-centering to the system. If dissipative devices or even more simple some reinforcing steel bars are located in the section where the pier rocks a sort of controlled dissipative rocking occurs during an earthquake. The technology will allow reducing the potential of damage to the sub and superstructures, while saving the functionality of the bridge after the earthquake. PRESSS programme [19] implemented this concept for the frame and wall systems, the extension of the concept to bridges happened with [20]. However, [21] implemented similar concepts of dissipative rocking bridge piers on rubber pads. Further studies in the United States (such as [22], [23]) followed on the single post-tensioned segmented bridge piers with and without supplemental dissipation devices. Recently, the University at Buffalo SUNY / MCEER has successfully tested a half scale fully precast segmental bridge (Figure 10) subjected to an earthquake of magnitude 7.0 Richter. The bridge remained functional with no structural damage after going under three shake table tests in both vertical and horizontal directions, [24].

Figure 10: Half-Scale Post-Tensioned Segmented Bridge System (after [24])

Figure 11: Comparison of Seismic Response of the Bridge Piers for the Hybrid and Monolithic Connections under Loma Prieta (1989) earthquake (EQ1)

Results from this research demonstrated that affordable mechanized technologies can drastically limit the damage in the pier, fusing the dissipation capacity in one or more critical rocking regions. However, this is not the major advantage, since all the above mentioned solutions demonstrated high self-centering characteristics in their hysteresis loops. But why is self-centering important? The question was raised by Kobe earthquake (1995) where several bridge piers, despite perfect compliancy with the current design standards suffered extensive damage with large permanent displacements/drifts beyond the reparable
limit. Japanese scientists believed that in order to achieve an enhanced structural performance, the residual permanent drift should be limited. One of the ways to achieve this goal was though the use of post-tensioning, [25]. Successively, the Japanese Seismic Code endorsed a check on residual drift. To highlight benefits of this technology, Figure 11 shows the advantages of a controlled rocking solution towards a traditional monolithic bridge pier. Both systems are designed with the same moment capacity. For the rocking system there is no damage of the structural member, similar maximum displacements as the monolithic, but zero residual permanent displacements/drift.

**Recent Developments at University of Canterbury**

Since 80s, University of Canterbury believed that rocking motion could be adopted as a sort of low damage technology alternative to traditional cast in place. [26] investigated pure rocking motion of a single bridge pier on its foundation while [27] proposed simplified design method.

However, dissipative controlled rocking experimental investigations at University of Canterbury followed the numerical work of [20] with an extensive experimental campaign on single 1/3 scaled rectangular bridge piers. Quasi static cyclic and pseudo-dynamic tests ([20], [28]) (Figure 12) on one and two directions with both internal and external dissipative devices confirmed the feasibility of the technology without increasing the construction costs respect to a traditional cast in place bridge substructure system. (Figure 12) shows technical details of the pier-to-foundation connection respectively with internal grouted bars and external dissipation devices, which similarly to Buckling Restrained Braces (BRB). Force-displacement cyclic hysteresis (Figure 12, top-right) clearly exhibits the so called flag-shaped profile which is typical of this technology. Tendons provide self-centering while bars or dissipaters add dissipation to the system.

![Seismic performance](image)

**Figure 12 – Controlled Rocking concept (top-right); solution with internal reinforcing steel (down-right); solution with external dissipation device (down-left); test results for solution with external dissipaters (after [28])**

[20] adapted Displacement Based Design Procedure for controlled rocking bridge systems, which have been successively refined by ([28]). Recent loss modelling analyses ([28]) confirmed the benefits of a low damage ABC technology. In fact, if a bridge system represents an important arterial route with limited detours the loss due downtime might exceed the cost of replacement.
From ABC to ABCD Advance Bridge Construction and Design (ABCD) into New Zealand Context

New Zealand bridge engineering community which comprises, Universities and research institutes, NZTA, KiwiRail, practitioners, contractors precast concrete producers and relative associations (CCANZ) has the competence and the structure to start a long term programme which doesn’t implement only ABC but also incorporates advanced low damage technologies combined with durable materials. Based on the New Zealand market trend, (Advanced Bridge Construction and Design) ABCD should mainly target low-medium span bridges (30 m maximum span) at this stage. Similarly to the precast decking solutions [15] recently supported by NZTA, different precast segmental bridge substructure systems need to be identified for different bridge span length, construction limits, i.e. maximum cost-effective crane limit, functional requirements.

Different bridge pier profiles (mono or multiple piers bent), pier-to-cap connections (fully precast or with partial wet joints), pier-to-foundation connections need to be properly detailed with two aims, optimizing construction speed and guarantee low post-earthquake damage. Possible design concepts are shown in (Figure 13).

![Figure 13: Concepts for ABCD decking-to-substructure](image)

ABCD bridges might be implemented combining precast post-tensioned substructure (self-centering capacity) with dissipative linkages which are activated by the relative displacement/rotation at the joint.

![Figure 14: Concepts for ABCD superstructure](image)
Existing linkages currently adopted in the retrofit programme [29] (Figure 14, left) can be slightly modified in order to become the dissipative fuses of the structure. Figure 14 (right) shows preliminary concept which needs to be properly detailed for each precast concrete deck.

Finally design methods Force or Displacement based, needs to incorporate all above mentioned features including foundation-soil-interaction. The new ABCD will also include interaction with non structural components, i.e. approaches balustrades, pipes etc., where especially for the latter, as learnt by the recent Canterbury earthquakes [1], the cost of disruption can be huge.

Another crucial aspect is to aim to a long-term resilience of the structure and this can be only achieved through a proper selection and combination of durable materials which intrinsically have also enhanced mechanical properties. For example, ultra and high performance concrete will also drastically drop cost of construction, while GFRC, CRFC or stainless steel post-tensioning will allow to reduce frequency of inspections and therefore the overall maintenance costs.

CONCLUSION

The intent of the paper is to provide a brief overview of international trends on Seismic Accelerated Bridge Construction (ABC) and face them to the current New Zealand bridge engineering practice. U.S. through FHWA, Caltrans and ASSTHO seems to strongly believe in ABC benefits and therefore a massive collaborative programme has been ongoing for 6 years. The U.S. researchers are currently working on new ways of improving the seismic performance of the bridges for ABC looking at both emulative cast in place and low damage controlled rocking solutions. The latter is more challenging but will be representing the next generation of bridges.

In the past decade, New Zealand had various “solo” of bridge engineering research, as briefly mentioned in the previous paragraphs, now it’s time for a “orchestra” which will certainly require major collaborative effort but will seriously impact for the next 20-30 years on the bridge construction and design at both national and international level.

REFERENCES

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