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Ultra High-Performance Concrete Column Jacket Retrofit for the Mission Bridge

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ABSTRACT

The Mission Bridge carries Highway 11 over the Fraser River between Mission and Abbotsford. It is a critical link in the Province's disaster recovery network, connecting industry, residents, and medical facilities between these two communities. The crossing is one of the Lower Mainland's major river and harbour crossings, for which the Province embarked on an ambitious seismic retrofit program, spurred in large part by the Loma Prieta earthquake in San Francisco in 1989 – 25 years ago this past October.

This bridge is founded on deep, liquefiable sands over a major river, and has many of the seismically vulnerable details and features found in bridges constructed prior to the 1980's. The bridge has been seismically retrofit and rehabilitated in several construction contracts performed over the past several years. Works completed through 2012 included structural seismic upgrades to provide enhanced deformation capacity, ground improvements such as compaction piles, stone columns, berms and other works, and superstructure rehabilitation and strengthening works. In 2012, the last seismic retrofit for the bridge was to densify the loose sands and silts at substantial depth to mitigate lateral spreading deformations of the south riverbank and the consequential damage to Pier S4. The propensity of the soils to spread laterally during seismic shaking, and the large (2.4 m) and very lightly reinforced rectangular concrete columns combined to create a significant seismic vulnerability and a high risk of damage or collapse from a moderate earthquake. A trial ground improvement contract near S4 was performed owing to the depth of soils being improved. The anticipated benefits to the soils for an economic layout and cost of compaction piles were not achieved, and alternative strategies were re-assessed.

The solution adopted was a combination of the geotechnical (ground improvement) benefits achieved by the trial compaction pile contract and column jacketing design to provide enhanced column deformation capacity. A new, innovative column jacket using ultra-high performance fibre-reinforced concrete (UHPFRC) was developed for the column ductility enhancement. The seismic behaviour of column jacket retrofits is well established, and use of UHPFRC to strengthen, improve spalling resistance, or improve durability of concrete piers is growing. However, to provide the necessary curvature ductility capacity to existing large rectangular columns, steel or concrete column jackets are typically stiff, large, expensive and visually obtrusive. The use of UHPFRC offered a solution to all of these concerns. This paper describes the options assessment and selection, the displacement-based seismic design approach, and the construction aspects of the ductility-enhancement retrofit for Pier S4 of this bridge. Materials use, quality assurance, and construction issues are discussed. This approach offers a new approach to retrofit that designers can consider for the retrofit of older, large rectangular concrete columns.

1. Introduction

The Mission Bridge 11 is a major bridge carrying Provincial Highway 11 over the Fraser River approximately 75 km east of Vancouver, B.C., Canada. The bridge connects the District of Mission and the City of Abbottsford in the Lower Mainland (Figure 1). It is classified by the Ministry of Transportation and Infrastructure as a “Lifeline” bridge, and is critical on the Region’s disaster recovery network.

In the years immediately following the 1989 Loma Prieta earthquake in San Francisco, the Province embarked on a seismic screening, prioritization and seismic retrofit programme for bridges on its highway network in the Lower Mainland and on Vancouver Island, two of B.C.’s highly developed regions and higher seismic risk zones. The application of displacement-based methods and performance-based design for the seismic retrofit of bridges was first applied in BC circa 1989 (e.g. Turkington and Kennedy, 1991), and has since been used on most or all major bridge retrofit projects since that time. As part of the seismic retrofit program for the Lower Mainland’s nine major crossings, in 1999 the Province retained Associated Engineering, with sub-consultants Klohn-Crippen (now Klohn-Crippen Berger) and TY Lin to perform a condition survey, seismic assessment and retrofit / rehabilitation design to upgrade and renew the crossing seismically and to maintain or extend it’s useful lifespan.

Figure 1 – Mission Bridge Aerial View Looking SE

2. Bridge and Site Description

The bridge connects the District of Mission and the City of Abbottsford in the Lower Mainland (Figure 1). The bridge and approaches is 1125 m long, and was opened to traffic in 1973. It comprises 22 spans, including 11 post-tensioned, precast concrete girder approach spans, eight steel I-girder approach spans, and three steel orthotropic-deck, trapezoidal-box beam spans with a 134 m long main span. All spans are supported on inclined-column concrete piers, designed for foundation cost savings and appearance. The bridge is founded on variable soils, including deep, loose and liquefiable granular soils throughout, and in particular in the river bank regions were grounds slope towards the river at grades in excess of 5%.

3. Background and Problem Statement

Associated Engineering, with Klohn-Crippen Berger as sub-consultants, carried out a detailed seismic assessment in the early 2000’s using evolving displacement-based methods. This confirmed that the bridge was badly deficient and unable to withstand large earthquakes Seismically inadequate detailing, liquefiable soils and lateral spreading, loss-of-span risk, and other seismic deficiencies required structural retrofits and ground improvements. Our displacement-based approach to assessment and seismic retrofit that was developed included extensive ductility-enhancing retrofits to piers, bearing replacement or elimination, restrainers and seat extensions, expansion joint elimination and bridge re-articulation and ground improvements near end fills and river banks. Extensive structural rehabilitation of the bridge, at least as important as retrofit, was also carried out in conjunction with the seismic upgrades.

Liquefaction at Pier S4 at the south river bank

One of the last seismic vulnerabilities to address was predicted one-time lateral spreading movements of about 400 mm of the Pier S4 foundation towards the river. This pier (Figure 2), located at the south river bank, had been structurally retrofitted previously with FRP jackets and concrete dowels to increase column shear capacity within plastic hinge regions, and to address seismically deficient column and pier cap reinforcing details.

Steel dowels with surficial plate washers were drilled and epoxied into the column cores within the bottom hinge zone as a conservative measure to increase confidence that a compressive strain prior to extensive spalling of 0.004 to 0.006 could be achieved. These column regions and their boundary conditions and assessed strain gradients caused concern that spalling could initiate at lower strains than would columns framing into orthogonal boundary elements, whether pier caps or foundations.

Figure 2 – Pier S4 (looking north-east) prior to retrofit with UHPFRC jackets

In our original retrofit design, the predicted liquefaction0-induced movement was addressed with ground improvements to reduce the peak displacement, an approach that had been successfully carried out at the north river bank and at other bridges in the Lower Mainland and elsewhere. The ground improvement design included stone columns and a combination of concrete and timber compaction piles. Figure 3 (Thavaraj, 2013) shows the zones of ground improvement that had been designed for the S4 region. The stone columns in Zones 3 were installed previously.

To confirm the driveability of concrete compaction piles, and to allow their spacing to be optimized, a trial contract of a small area of Zone 1 compaction piles was performed. The improvement in soil properties as measured using a CPT cone proved less than anticipated. An investigation and evaluation of the results was inconclusive, but showed that a tighter spacing of compaction piles, and hence an increased retrofit cost, was indicated. An alternative to the ground improvement was therefore sought that could reduce costs while providing reliable seismic performance.

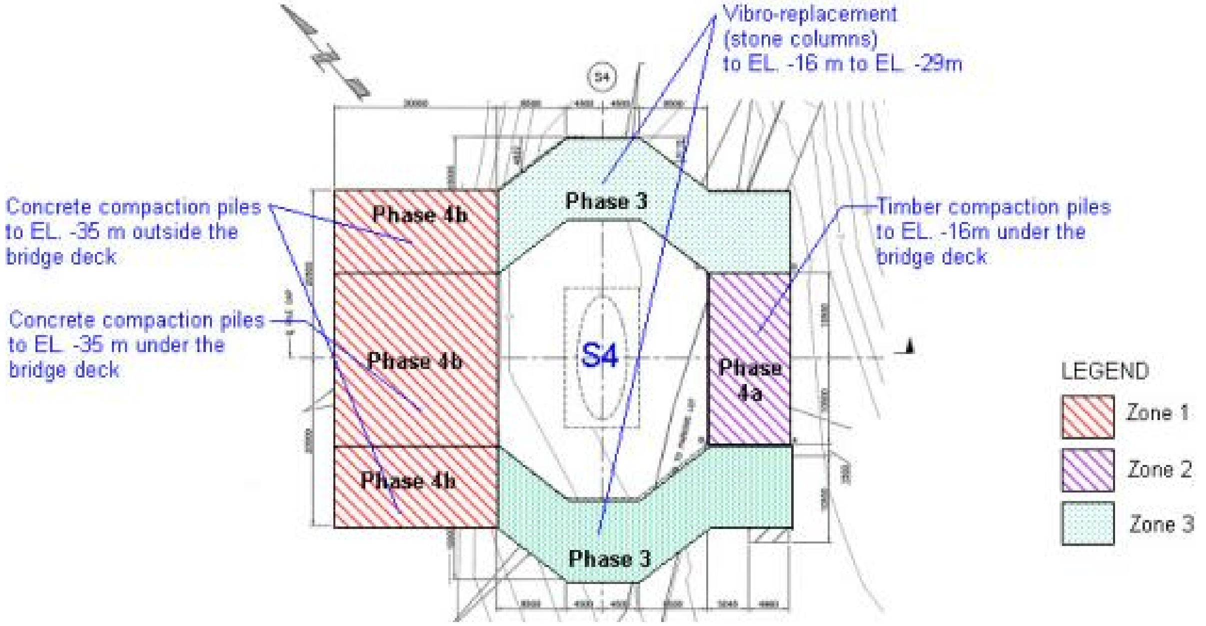

Figure 3 Original Ground Improvement Scheme at Pier S4 (KCB, 2013)

4. S4 Retrofit Concepts

With the ground improvement scheme found to have increased in cost to achieve the necessary reduction in lateral spreading, the Ministry asked whether alternative schemes be reconsidered. Both structural and soil-structure interaction options were considered, most having been examined previously as part of the retrofit strategy developed a decade prior. Possible options included:

1. Add ***vertical piles*** (914 diameter steel pipe piles) on the river bank side of S4 to stiffen the foundation against lateral spreading. The existing batter piles will cause a counter-rotation of the pile cap under lateral deformation, and new vertical piles would reduce this counter-rotation and increase the lateral stiffness. Figure 4 conceptually illustrates the new pile arrangement.
2. Install ***traditional confining jackets*** at the bases of the two columns to provide confinement and hence deformation capacity to sustain the large ground movements.
3. Install ***isolation bearings*** or seat extensions to the pier top to prevent loss-of-span collapse.
4. ***Devise a new column jacket*** system that could provide confinement without the physical and visual bulk of traditional reinforced concrete or elliptical steel shells.
5. Remove the concrete cover concrete and replace with a new, ***thin UHPFRC shell*** that could potentially provide enhanced spalling resistance, but without additional confinement benefits, and potentially add deformation capacity to the columns (Massicotte et al, 2013)

Option 1 was studied in detail using non-linear FLAC analyses to capture liquefaction, lateral spreading, and soil-pile interaction. These analyses showed that they would be at least as effective as a ground improvement approach, but was rejected owing to cost and construction risks. Option 2, steel or concrete confining jackets, would be structurally very effective (Priestley et al, 1992, Anderson et al, 1995) but relatively expensive and extremely large. Elliptical steel shells would have diameters approaching 3.6 m (11.5'), which would also be visually massive and was not desired at this popular waterfront park. Option 3, isolation bearings, had been studied previously and had been rejected. Our updated review confirmed this decision. Option 5, thin UHPFRC shell is well proven for small columns and spalling resistance, but untested and unlikely to provide adequate deformation capacity for a large rectangular concrete column. Failure of this pier owing to an unconservative deformation capacity would jeopardize the seismic resilience of the entire crossing.

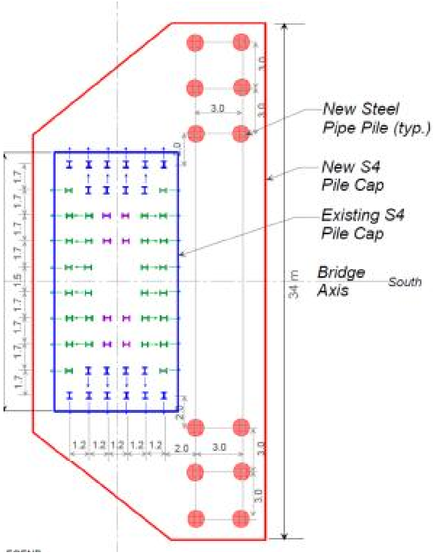

Figure 4 Soil-Structure Interaction Concept with Vertical Pipe Piles (KCB, 2013)

Option 4, a concept comprising a relatively thin but stiff and structurally robust UHPFRC column jacket, evaluated carefully for cost, reliability, and its potential to provide a new, innovative and effective approach to column jacketing for large rectangular or square concrete columns.

For a column ductility approach, our design objective was to provide a deformation capacity of at least 800 mm and preferably larger, i.e. two to three times the estimated displacement demand due to liquefaction. This option would require jacketing of the columns for confinement, and was found to be the most cost-effective option. A UHPFRC jacket was estimated to have similar cost to steel or concrete jackets, but needed to be designed and detailed to provide the necessary stiffness and confining pressure capacity. This approach is a good example of a displacement-based approach to achieving a performance-based design specification for a retrofit of an existing, otherwise brittle sub-structure.

FRP jackets and dowel retrofit had been installed in earlier retrofit phases for shear enhancement in hinge zones, but were not expected to nor required provide significant additional confinement or sufficient deformation capacity, had ground improvement been installed and shown to be effective. Therefore, the possibility of a substantially thinner jacket, capable of providing the confinement pressures and internal stiffness using ultra-high performance fibre-reinforced concrete (UHPFRC) was assessed and ultimately designed and tendered for construction.

5. UHPFRC Jacket Design

For the S4 columns, a 225 mm thick UHPFRC jacket was assessed and designed. The jacket philosophy is based on work by Priestley during his time at UCSD in the late 1980's and early 1990's (Priestley et al, 1992). A gap is left between the jacket based and pile cap to allow the column to hinge plastically, and the jacket above confines the column above this localized hinge. Testing of jackets on rectangular column, including half-scale tests done on the Oak Street Bridge pier columns (Anderson et al, 1995), demonstrated reliable, repeatable displacement ductility capacities in the range of 10 to 12; potentially as high as that achieved in the design of modern new columns. Larger columns require proportionate confining pressures, which place increasing demands on the larger column jackets.

For Pier S4 columns, 15M reinforcing bar dowels between the jackets and column cores were installed at roughly 230 mm centres in both directions. Most of these dowels were installed as part of the original FRP jacket retrofit as discussed above. These dowels, in combination with the corner regions of the UHPFRC concrete shells, were sized to provide the necessary confining pressures using column jacket design expressions developed by Priestley. While the UHPFRC jackets without such dowels would be sufficient for many columns, and appeared adequate for this application, the existing dowels were used and enhanced as a conservative, simple and low-cost measure for overall reliability and to increase jacket's post-cracking stiffness against core concrete dilation.

The addition of mild-steel reinforcing bars within the UHPFRC jackets may not have been strictly necessary, but were expected to improve crack distribution, post-cracking stiffness, and resistance to cracking from jacket restraint. They also allow lower steel fibre content without causing premature failure of the jacket by formation of a single or few localized cracks (Habel, 2004). To the project team's knowledge, the application of UHPFRC for a seismic confining jacket of a large rectangular column was the first worldwide. In addition, there are currently no test results or research results for using UHPFRC for column seismic retrofits of this size. Therefore, the design intentionally did not fully exploit the tensile capacity and stiffness of the UHPFRC material or jacket. The UHPFRC used for the project was Ductal by Lafarge and incorporated 12 mm long thin and straight steel fibres at 2% by mass, which produced a marginally strain-hardening material under bending. Since this was the first application of UHPFRC with the Ministry of Transportation and Infrastructure in BC, a UHPFRC trial was successfully carried out to simulate placement at the bridge site and to obtain material specimens for compression, bending and shrinkage tests. Material and construction aspects are outlined following.

6. UHPFRC Material and Specification

UHPFRC is a fairly recent class of advanced cementitious materials with improved strength and durability properties when compared to normal strength concrete. UHPFRC traditionally consist of cement, silica fume, fine quartz sand, superplasticizers and steel fibers with water/binder-ratios ranging between 0.15 and 0.25 (Russell and Graybeal 2013, Habel 2004). However, multiple variations of UHPC matrices have been developed in recent years, which contain other supplementary cementitious materials and sometimes also coarser aggregate. The main characteristics of UHPFRC are achieved through the following three principles (Richard and Cheyrezy, 1995):

- *Homogeneity enhancement* by eliminating coarse aggregates in the matrix,
- *Density enhancement* by optimizing the packing density of the matrix. This is achieved through optimizing gradation and mix proportions between the main matrix constituents.
- *Ductility enhancement* by introduction of fibers: As the matrix is very brittle, fiber reinforcement is added to obtain elastic-plastic or strain-hardening behavior in tension.

The optimized mix design of UHPFRC leads to very advantageous material properties when compared to normal strength concrete and traditional fibre reinforced concrete. UHPFRC typically exhibit elastic-plastic or strain-hardening characteristics under uniaxial tension and have a very low permeability due to their dense matrix for site cast mixes without heat or pressure treatment. They usually have a compressive strength of about 150 MPa to 170 MPa, a secant modulus of 45,000 to 50,000 MPa, and a tensile strength in the range of 6 to 10 MPa.

The tensile behavior of the material is strongly influenced by the amount and type of steel fibres used. Typically, a fiber content of more than 2 Vol.-% is required to obtain strain-hardening behaviour. Thanks to the addition of steel fibres, UHPFRC also have a significantly higher energy dissipation capacity under tension within the material, which is particularly beneficial in seismic and impact-type applications. The fibres embedded in the UHPFRC significantly reduce spalling under dynamic or cyclic loading (Habel and Gauvreau, 2009). Adding reinforcing bars into the UHPFRC further improves the behaviour of the material: development length and anchorage of reinforcing bars in UHPFRC is significantly shorter than in normal strength concrete. The tension stiffening effect of reinforcing bars leads to even more finely distributed fine cracks than in plain UHPFRC, and the energy dissipation capacity and ductility of the system are further increased.

UHPFRC is typically self-compacting, which allows for easy placement and fairly equal fibre distribution.

The UHPFRC used for the seismic retrofit of Pier S4 was Ductal JS1000 or approved alternate with an approximate mix design of:

- Premix (binder and aggregates): 2195 kg/m³
- Water: 130 kg/m³
- Super Plasticizer Liquid: 30 kg/m³
- Steel Fibres: 155 kg/m³

The amount of steel fibres corresponded roughly to 2% by volume, and relies in part in this case on supplemental mild steel rebar for added crack control and distribution behaviour.

7. Construction

Construction of the column was carried out in the summer of 2014. The on-site construction was carried out as follows: The first step of construction was to remove the existing FRP wrap and roughen the surfaces of the existing concrete where new concrete or UHPFRC was to be installed. Then, the pedestal was widened with traditional reinforced concrete in order to force hinge formation under a seismic event to the gap left at the bottom of the columns. The cross-section at the bottom of the column was also weakened with a notch and cutting of selected longitudinal bars to capacity-protect the column and pedestal. As discussed above, steel dowels were embedded into the existing column and into the UHPFRC jacket to tie the UHPFRC jacket to the column and increase and stiffen the confinement (Figure 6). Reinforcing bars were installed, and finally the UHPFRC was cast into the formwork.

Figure 6 – Pier S4: Column preparation with sandblasting and installation of dowels

The UHPFRC for Pier S4 was mixed at the Lafarge plant in Abbottsford, BC, and transported to site in a traditional concrete truck. Casting of the self-compacting UHPFRC was carried out with traditional means with a bucket as shown in Figure 7. It should be noted that the UHPFRC mix design used did not include any accelerator and that setting of the material had a delay of approximately 24 hours. This can be reduced if necessary through the mix design and addition of appropriate admixtures.

Figure 7 – Casting of UHPFRC jacket

Since this was the first application of UHPFRC for a seismic retrofit in British Columbia, we stipulated that the Contractor carry out a trial batch and trial casting prior to casting the UHPFRC on site. This trial was intended to test batching and casting procedures to assure adequate performance during production casting of the UHPFRC at Pier S4. The UHPFRC for the trial was produced by Lafarge in Abbottsford, BC, under the same conditions as the UHPFRC used on site. During the trial, a wall of the same height and thickness as the final column jacket and of 1000 mm width was successfully cast. In addition, flow tests were carried out on the fresh material, and specimens were cast for compression, length change (shrinkage) and bending tests. The flow and compression tests were compliance tests, required to pass certain criteria prior to casting of the UHPFRC in the bridge. The length change and bending tests were specified to provide us with data for future designs, since the design did not rely on the results of these tests. Figure 8 shows the results of the flow test during the trial batch, indicating a self-compacting mix.

Figure 8 – UHPFRC Flow Test

Quality control tests for fresh UHPFRC flow and for compressive tests were carried out for the UHPFRC for each truck load used during casting of the jackets. The flow tests confirmed that the material was self-compacting as intended. The average 28 day compressive strength was 148 MPa for specimens cured similar to the field conditions. Construction was carried out smoothly and successfully. The final retrofit, shown in Figure 9, provided an unobtrusive solution when compared to other jacket types, and complements the other

Figure 9 – Pier S4 after Completion of Construction

8. Conclusions

The installation of the UHPFRC jacket was carried out smoothly and without any significant construction issues on site. The UHPFRC was cast for both columns in one day. This material and innovative approach provided a thin seismic jacket retrofit for Pier S4 using a confinement solution for a relatively large rectangular column. It offers the potential for cost effective and thinner jackets on even larger bridge piers, where other options simply would not be practical or desirable. Traditional jackets, whether elliptical steel shells or thick reinforced concrete jackets, are technically viable but would be visually obtrusive at this prominent site, and offer no cost advantages over the UHPFRC approach. The UHPFRC jacket design approach we adopted is based on an established and proven displacement-based method first proposed by Priestley (1992) and shown through testing to provide ductility through confinement to plastic hinge zone, with plasticity and eventual concrete failure and rebar local fracture within a gap region at the base of the column. Despite the concentration of plasticity, the strategy is proven as effective. The approach we adopted using UHPFRC was novel and untested, and therefore was approached conservatively to reliably address the large pier deformation expected due to liquefaction and lateral spreading. This retrofit was the last structural phase for the seismic safety retrofit of the Mission Bridge and brought this important bridge renewal project to a successful conclusion.

Acknowledgments

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References

Turkington, D,. Kennedy, D, 1991. Seismic Assessment and Retrofit of the Vancouver Oak Street Bridge", Pacific Conference on Earthquake Engineering, Auckland, New Zealand, November.

Priestley, M.J.N, Seible, F., Chai, Y.H. 1992. Design Guidelines for Assessment, Retrofit and Repair of Bridges for Seismic Performance, SSRP – 92/01, UCSD.

Priestley, M.J.N., Seible, F., Calvi, G. M., 1996. Seismic Design and Retrofit of Bridges, John Wiley and Sons.

Anderson, D., Sexsmith, R., English, D. Kennedy, D., and Jennings, D., 1995. Oak Street & Queensborough Bridges – Two-Column Bent Tests," University of British Columbia Department of Civil Engineering, Earthquake Engineering Research Facility Technical Report 95-02, July.

Thavaraj, T., Seismic Deformation Analyses of South River Bank (Mission Bridge), 2013. Technical Memorandum, Klohn-Crippen Consultants to Associated Engineering (on behalf of the Ministry of Transportation and Infrastructure of B.C., unpublished).

Habel K., 2004. Structural Behaviour of Elements Combining Ultra-High Performance Fibre Reinforced Concretes (UHPFRC) and Reinforced Concrete. Doctoral Thesis No 3036, EPFL, Lausanne, 2004.

Massicotte, B., Dagenais, M.-A., and Lagier, F., 2013. "Strengthening Bridge Piers using Ultra High Performance Fiber Reinforced Concrete.", Seventh National Seismic Conference on Bridges & Highways (7NSC), May 20-22, Oakland, California.

Russell, H.G., Graybeal, 2013. B.A., Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community, Report FHWA-HRT-13-060, Federal Highway Administration, McLean, VA, June.

Richard P., Cheyrezy M., Composition of Reactive Powder Concretes, Cement and Concrete Research, Vol. 25, No. 7, October, 1995, pp 1501-1511.

Habel K., Gauvreau P., Behavior of reinforced and post-tensioned concrete members with a UHPFRC overlay under impact loading, ASCE Journal of Structural Engineering, Vol. 135, No. 3, March 2009, pp. 292-300