Te Rewa Rewa – A Bridge that really connects

For bridges to give dignity to their setting they must first be built with dignity

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Figure 1: ***Te Rewa Rewa*** **Bridge with Mount Taranaki in the background. The bridge allowed the extension of the existing New Plymouth Coastal Walkway to cross the Waiwhakaiho River and be extended to the suburb of Bell Block.**

There is very little written about the creative process as it pertains to bridge design. As a designer, I've learned to dissect the thought processes needed to develop a design concept for whichever project is before me. So it was with the Te Rewa Rewa shared pathway bridge.

I have defined the creative process for bridge design as being made up of three advancements. The first is from the mind of the designer onto paper by making sketches. The second is from these sketches to engineering drawings. The third advancement is from the drawing board to the wonder of a wholly completed bridge. It's the first advancement that will be my focus here.

During the first advancement, an engineer must hold multiple visions of the bridge in his mind's eye. These are sometimes described as 'a four-fold vision of the project, simultaneously considering issues of structural form, mathematical analysis, construction methods, and the relationship of the structure to the site.' (1) Personally, I have renamed and reordered these to reflect my experience of concept development with the Te Rewa Rewa Bridge. They become structural form, construction method, contextual setting and analytical modelling. These are neither sequential nor simultaneous, but more a series of reappraisals of each vision until the final concept has been developed.

During the structural form vision stage, a designer selects a classical bridge configuration to suit span and deck alignment. Because a clear span of 70m and a minimum deck soffit height of 4.5m above normal water level were needed for the Te Rewa Rewa site, I chose a single through-deck arch. Statistically, this resulted in the lowest steel weight and cost for a span this length. (2) The contract for procurement required an iconic bridge on an extremely modest budget. (3). These two contradictory requirements had significant bearing on conceptual design choices.

The construction method vision became a refinement of the structural form, and considered the bridge site conditions, the contractor's experience, preferences, resources and facilities. With a very experienced oil and gas steelwork fabrication workshop just 1.5km away from the Te Rewa Rewa site, I selected a tied arch configuration so the superstructure could be fabricated in workshop conditions and transported to site as one element. The geotechnical investigation revealed underlying layers of volcanic boulders on site, with good ground bearing characteristics but which are notoriously difficult to pile through, so heavy concrete abutments on pad footings were selected. Ready access to low cost volcanic (andesite) boulders from the contractor's own quarries, provided the scour protecting rip rap for both abutments.

Contextual vision is an acknowledgment that a bridge will be part of its environment and must give dignity to its setting. It can reveal to observers what its owners and designers had strived to create. This vision is used to both fine tune and add something special to the two previous visions, and it's where the bridge character and deeper meanings are truly expressed. The Te Rewa Rewa site clearly deserved an iconic bridge. (3) As a designer I understood the more ancient meaning of the word 'icon' – a symbol to draw worshippers into a deeper reality, instead of the modern meaning of simply being popular. The Te Rewa Rewa Bridge leads to - and gives public access to – the sacred land of the Te Ati Awa iwi (the main local tribe) and Ngati Tawhirikura hapu (the local sub-tribe), whose descendents were killed and buried there. During the Musket Wars (1820 to 1830) and the Taranaki Wars (1860 to 1863) it had been a battlefield until unjustly confiscated by the Crown. For most of the 20th century, it had been used as a rifle range with limited public access, until reconciliation between the *iwi* and the Crown resulted in co-management by both *iwi* and the New Plymouth District Council. For me, it was the poetry of James K Baxter, arguably this country's greatest literary talent, who provided the true inspiration. As poet and contextual theologian, it was Baxter who persuaded me to try and capture a sense of the wind, with his idea of transformation as a metaphor for the spirit, or *wairua*, of the souls of the dead. This led me to design a series of curved hangers or ribs, asymmetrically connecting the deck to the arch, and aligning the arch diagonally across the deck to form a gateway, or *waharoa*, signifying to the observer that he or she was about to enter or leave sacred land.

The fourth vision determines the series of analytical models to be used to aid understanding of the structural behaviour of what had become a complex and unique form. It verifies the three previous visions and confirms in the designer's mind that his development remains structurally valid, with well defined load paths that will result in a functional bridge.

Project Background

To understand a project is to realise how it came about. In October 2007, the New Plymouth District Council (NPDC) as client requested a registration of interest from Design and Construct (D&C) consortiums for the Waiwhakaiho River Crossing lump sum contract. (3). The crossing was to extend the existing popular Coastal Walkway and to divert pedestrian and cycle traffic from the congested public road between New Plymouth and the suburb of Bell Block.

Three D&C consortiums were selected to tender. The two main weighted attributes for selection were price and design, each of which held equal weighting of 30%, while other attributes such as track record, relevant experience, technical skills, resources, management skills and construction methodology had between 5% and 9% weighting each.

Tender documents called for an iconic bridge to be simultaneously beautiful and utilitarian. (3) The bridge was to be a delight to the eye and, out of respect for the descendents of the Ngati Tawhirikura buried there, touch lightly on the Te Rewa Rewa side of the Waiwahakaiho River. The bridge was to respond to the landscape as well as the social and cultural heritage of the ancient site.

The bridge site stood 300m upstream from the river mouth, and the bridge itself was to be 3m wide between 1.2m high balustrades. It was to clear span the river with a span of 70m, and there were to be neither permanent nor temporary piers in the waterway, which stretched approximately 50m wide at normal flow. The deck soffit was to stand a minimum of 4.5m above normal river level, which meant it should clear the surrounding flood plain by approximately 2m. The bridge was to be designed in accordance to the loadings and codes referred to in the Transit New Zealand Bridge Manual (4) but in the event of emergency, it could provide passage for a 3.5tonne ambulance between New Plymouth and Bell Block.

During the period from October 2007 to mid-January 2008, the preliminary design of the Te Rewa Rewa Bridge was conceived and priced as a lump-sum project. It was decided, after contract award, that the deck should be aligned with the summit of Mount Taranaki, which rises 2,518m high and dominates the Taranaki landscape.

<u>Design and Construct Team</u>

The contract went to a team with a strong New Plymouth-based presence. The author held the reigns as lead designer, bridge designer and design manager. Whittaker Civil Engineering Ltd (WCE) in the roles of contract manager, site manager and environmental manager, CPG (New Plymouth Ltd) as quality manager. Fitzroy Heavy Engineering Group Ltd (FHEG) became the steel fabrication sub-contractor because of their world class reputation and their workshop was located close to the bridge site.

Numerous other sub-contractors, typically with a strong local presence, added to the project – and all parties seemed to know they could add something poignant to their city.

Due to budget restraints, Te Rewa Rewa Bridge project was engineer led, though both competing D&C teams had architects in their teams.

<u>Concept Development</u>

The Te Rewa Rewa bridge concept needed a four-fold final vision to be kept in the designer's mind's eye. Though the four visions have been categorised and detailed and divided into four distinct categories for explanation purposes, the reality is they had overlapping boundaries, particularly where structural form, construction method and contextual setting is concerned.

The bridge form, selected from the first three visions, proved to be highly asymmetrical and unique. In order to be priced properly for tender, it underwent deconstruction until it became a series of simple analytical models for preliminary design and member sizing. This analytical modelling provided the fourth vision.

It was decided early on by the project team to wholly fabricate the steel tubular superstructure of the Te Rewa Rewa Bridge in the FHEG workshop, and then transport it as one large element to site. This lowered costs, ensured the fabrication was to the highest standard and meant there would be no need for site welds or bolted joints. All protective coating work could be completed in controlled conditions. The only bolted joints made on site were in the balustrades, which were fixed in place after the superstructure and the precast concrete deck panels were in place on site.

It should be noted that transporting the 85m long, 85tonne slender, asymmetric superstructure required further analysis during the detailed design phase to determine centre of gravity, lifting and supporting points and temporary bracing requirements.

The most important visions for the development of a design concept are the structural form and the contextual setting. In particular, these two visions have considerable overlap and could possibly be considered one combined vision. The structural form could be considered the 'engineer's' vision and the contextual setting the 'artist's' vision, though as designer, I've never claimed to be an artist.

Vision 1 – Structural Form

Given the 70m clear span requirement (3) an arch form was selected, because according to statistical information (2), the estimated weight of steel would be in the order of 0.35t/m2. A truss superstructure would require a similar quantity of steel. At an early stage of the design process, I felt there was more opportunity for an arch structure to be contextualised into the setting, though I initially gave the truss consideration as it had on-site assembly advantages over the arch. These advantages were eliminated after it was decided to reduce costs through workshop fabrication and transporting the superstructure as one element to site. A truss, by its nature, has edges and angles that create disquiet and confusion to pedestrians who view, touch and feel the bare structure at close range and slow speed. (5) Given the violent history of the Te Rewa Rewa site, followed by recent reconciliation, I wanted to create a harmonious and peaceful experience for people as they crossed the bridge.

Figure 2: *Te Rewa Rewa* Bridge with the deck aligned to the summit of Mount Taranaki. The bridge spans the Waiwhakaiho River at a location approximately 300m from where it flows into the Tasman Sea.

A cable stayed bridge configuration for a 70m clear span would result in an estimated steel weight of 0.45t/m2. (2) The likely increased weight – and therefore, cost – over an arch provided the first reason to rule out this option. The site is very exposed, with strong prevailing westerly winds coming in over the Tasman Sea. This inherently slender structure would be subjected to both pedestrian and wind-induced excitation. The prospect of a cable-supported slender deck, that had to comply with the vibration serviceability criteria of B55400-2; 2006 Annex B provided a second reason to rule this option out. With very few cable bridges in New Zealand, and based on my previous experience designing cable structures, the price of a cable bridge was prohibitive for the scale of the project, and became the third reason for ruling out the cable stayed configuration.

The client's desire to have the end of the bridge 'touch lightly' on the Te Rewa Rewa side of the river out of respect for the deceased, coupled with the prospect that there could be no permanent piers in the waterway, also meant the cable stayed option with the main pylon on the city side was ruled out. After a site visit, I had the distinct feeling that the New Plymouth side of the bridge was the Pākehā (European descendent) side and that the Re Rewa Rewa side was the *Māori* side. A tall pylon dominating the site might be seen as a symbol of Pākehā triumph, and give the opposite character to what the client had requested.

Instead, I chose an arch with a span-to-rise ratio of 10. A low arch would appear respectful and not dominate the low hills of the *Pā* site. Today, the arch frames the site when the observer approaches the bridge from the coastal walkway on the city side of the river.

To avoid triangulated lateral arch bracing, for the same reason as a truss option was dismissed, I selected a single, wide arch. To avoid expensive arch fabrication, a large circular hollow core (LCHS) section was chosen. This could be curved by induction bending to form the parabolic profile. I avoided using a faceted arch because the mitre joints would distract the observer. The range of LCHS available gave sufficient scope to select a suitable diameter and vary the wall thickness according to load demands.

The plane of the arch is in the vertical plane where it is most efficient. To complement the tubular arch, I decided the deck structure should be tubular also. Because the arch is vertically stiff to support the deck, the deck had to be laterally stiff to provide lateral restraint to the arch and prevent buckling. I then decided that a tubular member should be used to trim each side of the deck structure. These members would also provide a tie between the arch springing points.

The basic superstructure skeleton was therefore to be three tubes – which became the arch, heel and toe tubes, after the shape of the frames connecting them had been devised (see the contextual setting below). These were sized to provide sufficient torsional stiffness, in addition to their requirements to carry axial and flexural actions. Because of the exposed site, great consideration was given to wind-induced vibration. Vertical, horizontal and torsional modes of vibration were achieved. The fundamental mode of vibration was 1.3Hz in the torsional mode. The first horizontal and vertical modes surpassed the requirements of B55400-2: 2006 Annex B.

The deck material selected was to be 50MPa concrete with 500MPa reinforcement for durability, strength and the ability to enhance the lateral stiffness of the deck by diaphragm action. Hardwood timber and steel grating were also considered but dismissed because they would require diagonal bracing on the underside to provide the necessary deck stiffness. All angularity was avoided.

Geotechnical investigation bores at both abutment sites revealed deep layers of small to large volcanic cobbles intermixed with medium to coarse gravels and sand. Raymond numbers (N) exceeding 40 were common to considerable depth. This country is notoriously difficult to pile if large boulders are encountered. Heavy mass concrete abutments on large pads were used to provide adequate ground bearing, while relying on base friction and lateral earth pressure from scour protecting rip rap to resist lateral actions were selected.

The ground conditions provided extremely good bearing with only small amounts of settlement and abutment rotation possible. Over the 70m span, the likely differential settlement between abutments would have a negligible effect on the superstructure. This was the basis for deciding to fully cast the true right end of the superstructure into the abutment, and only provide elastomeric bearings under the superstructure on the true left abutment. Elastomeric bearings were selected for their simplicity and durability, and sized to carry the vertical loads and to accommodate the thermal expansion and contraction.

Vision 2 – Construction Method

In order for the arch superstructure to be transported to site as one element, it had to be tied arch to prevent the springing points (ends) spreading. With the site design requiring mass concrete abutments (see above) while pursuing a skewed arch relative to the deck for contextual reasons (see below), a steel springing was needed to connect the ends of the arch and the deck at both ends of the superstructure. The steel springing would then be embedded in the concrete springing. (The true left steel springing can be seen on the right of Figure 3.) To prevent distortion of the superstructure due to the vertical and transverse eccentricity of the arch relative to the heel and toe tubes, temporary diagonal deck bracing and tension ties were designed for transportation.

The deck panels are full depth precast units simply supported between 19 evenly spaced cantilever beams coincident with the ribs. In order to utilise the diaphragm action of the panels for lateral stiffness, galvanised and waterproofed linkage hooks were cast into in situ stitches above each cantilever. Connection between the stitch and the cantilever was made by shear studs. To prevent concrete shrinkage distortion of the cantilevers, the panels were all cast and cured for at least 150 days before being cast onto the superstructure. Almost all of the expected lifetime shrinkage had occurred prior to connection to the deck superstructure.

Figure 3: The *Te Rewa Rewa* Bridge superstructure being transported to site from the fabrication workshop. The superstructure as shown was approximately 85m long and weighed 85 tonnes. The journey distance was 1.5km across mainly unpaved tracks.

Vision 3 – Contextual Setting

The single most important aspect of the bridge site was the fact that it led to sacred land for the Ngati Tawhirikura hapu. This *whenua* (land) is the home of their *tupuna* (ancestors). They are buried there and their *wairua* (spirit) still dwells there. The bridge design had to acknowledge the spiritual value of the site for the *tangata* (people) with *mana* (prestige, authority, control, spiritual power) over the land.

To capture a sense of the spirit and the mystery surrounding the site, without usurping or falsely mimicking any traditional Māori customary architecture, was an essential aspect of the bridge design.

Overarching all the violence and suffering of the *Ngati Tawhirikura hapu,* was the Parihaka Movement (www.parihaka.com) which has become significant for all Māori of the Taranaki region. The Parihaka Movement embraced non-violent resistance to post-Taranaki War land confiscations by the Crown and was led by two Taranaki prophets, Te Whiti o Rongomai and Tohu Kakahi, 50 years before Mahatma Ghandi advocated non-violent resistance in India. Throughout a 19-year period, from 1879 to 1898, Te Whiti, Tohu and their warriors were arrested and imprisoned without trial. The symbol of the movement, the *raukura* of three white *toroa* or albatross feathers, is still adopted today by Māori in the Taranaki district. It represents spirituality, the importance of making peace within you and with others, and the necessity of maintaining goodwill despite conflict.

Not only was the bridge to invoke a sense of historic mystery, it was to engender a feeling of peace and harmony. I had once read a story about Michelangelo in the 16th century, who had reasoned 'bridges should be built as though they were cathedrals'. While I have not been able to find a reference to this quote, this thought of Michelangelo's added to my feeling that this bridge could, in a sense, be a place of meditative worship for a largely secular and un-churched society which relates readily to the radical openness of the outdoors.

To help signify to the observers that the bridge allowed access to sacred land, a *wahaora*, or gateway, was considered pertinent. Conscious not to mimic traditional Māori structures and risk offense, I decided to skew the arch diagonally across the deck. This skewed arch would form a subtle gateway over the long, narrow deck, beginning at the left shoulder and finishing at the right shoulder as people crossed the bridge. This would give the effect of walking under the arch, and promote a sense of transition, not just of the physical transition from one river bank to the other, but of a social transition between the urban Pākehā, and traditional Māori land, as well as a generational transition between *tupuna* (ancestors) and *mokopuna* (future generations).

To connect the vertically stiff arch with the laterally stiff deck system required hangers. The most effective method was to use two planes of steel rod cross bracing from the arch to each side of the deck. These would provide efficient vertical and lateral restraint to the arch, prevent buckling in those planes and also provide a torsionally stiff truss. Eventually, rod bracing was dismissed for two reasons: The inclined bracing would impinge on the clearance envelope for the ambulance, cyclists and pedestrians, and for the same reason the truss superstructure option was dismissed. That is the angular and industrialised nature of the bracing would detract from the wish for peace and harmony.

Inspiration for the 19 curved ribs came from aspects of nature associated with the site, and the poetry of James K Baxter, which uses the wind as a metaphor for the souls of the dead. With the bridge on a general north-south alignment, and the prevailing wind coming from the west, the ribs curved as if blown by this wind. The curved ribs, combined with the skewed arch alignment, provided Te Rewa Rewa's most unique and compelling feature. (See figures 1, 2 & 6.)

The curved ribs allowed suitable clearance envelope to be achieved and provided a flexural and tensile connection between the arch and the heel tube along the downstream side. To allow for the evenly distributed introduction of stresses into the arch and heel tubes, they both have thick doubler plates to spread the loads from the narrow ribs to the large thin-walled tubes.

The skewed arch results in all the ribs being a development of adjacent ribs. Their form and repetition emulate nature where no straight lines or identical objects exist. This repetition technique is often used in places of worship to promote harmony.

The observer walks along the bridge and a poetic tension accentuates the feeling of transition. As he approaches from the New Plymouth side of the walkway, along the true left bank of the river, the bridge appears to be a conventional, with the ribs seemingly vertical. As he draws nearer, the perspective becomes more oblique as the ribs become a curved surface. The ribs continue past the heel tube to support the deck in a series of 19 cantilever beams terminated in the longitudinal toe tubes. The ribs cum cantilever frames run parallel to the normal flow of the river and are at a 10 degree skew to the heel and toe tube alignment.

When on the deck, the bridge skeletal structure is very open with little obstruction. Yet the ribs of the downstream side create a sense of shelter, protection in contrast to the upstream side which offers an unobstructed view of the *Pā* site.

The skewed arch relative to the deck alignment results in large torques about the vertical axis at each abutment due to the transverse eccentricity of the arch thrust and deck tension. The abutment imposed torque is resisted by base friction and lateral earth pressure from the surrounding scour protecting rip rap. The true left abutment is the free end with the concrete springing being allowed to move longitudinally and is vertically supported on three elastomeric bearings. In order to carry the torque from the true left concrete springing to the abutment, two transverse thrust blocks under the concrete springing were designed. These are inside the inspection gallery and bear onto a single elastomeric bearing each. The elastomeric bearing allows longitudinal movement to occur due to temperature variation. (See Figure 1 to view the front thrust block under the true left springing.)

Making connections and relationships between the structural ribs and contextual setting of the bridge were the most creative and possibly the most artistic aspects of this project. These connections provide a deeper and more profound meaning for local people.

Painting the bridge white linked with the *raukura*, (some observers see the bridge as a feather), with snow on Mount Taranaki and aligned the deck to the summit in order to frame Taranaki. To quote Baxter, 'Jagged peaks covered with an altar cloth of snow. A silent witness to what is eternal'.

Figure 4: The historic *Te Rewa Rewa* Pā (fortified village) site on the cliff over the Waiwhakaiho River upstream from the bridge.

Figure 5: The coastal horizon and the natural flood channel of the Waiwhakaiho River showing the proximity of the bridge to the Tasman Sea.

Vision 4 – Analytical Modelling

The first three visions contribute to the final form of the bridge structure. The fourth vision of analytical modelling is to verify the overall concept is valid. A series of simple models was selected to understand the behaviour of the slender and asymmetric structural concept to be developed. For the most part, these models allowed a preliminary design to be completed with manual calculations, which were checked against more sophisticated, finite element analysis.

I employed classical arch theory to determine axial loads in the arch tube and flexure under an asymmetrical half-span loading. The effective length for the critical out-of-plane buckling condition was determined using a beam-on-elastic foundation model. The flexural cantilever stiffness of the ribs, the torsional stiffness of the steel deck structure and the transverse stiffness of the deck were considered as providing stiffness to the ribs as a series of partial lateral restraints.

The transverse actions on the deck due to vertical loading were determined by considering the deck as having pendulum action suspended under the arch. With arch aligned on a diagonal across the deck almost from corner to corner, the net effect was dependent on the distribution and magnitude of vertical loading. The lateral loads were carried into the abutments by transverse shear.

As previously mentioned, the skewed arch meant large torques, about the vertical axis, were imposed on each of the abutments. Three components of deck structure carried the counteracting tension between abutments – the heel tube, the longitudinal linkage bars through precast concrete deck, and the toe tube. The relative axial stiffness of these components can be used to determine the transverse eccentricity of the applied torque. The torque resistance due to base friction and lateral earth pressures is relatively straightforward to obtain.

Due to the complex geometry, the exact position of potential plastic hinges from seismic excitation was difficult to reliably predict and therefore a low ductility and elastic response was considered. Because of the structure's low weight, this was not a governing design criteria.

Figure 6: An aspect of the *Te Rewa Rewa* Bridge showing the tubular arch forming a gateway. The coast horizon of the Tasman Sea is in the background.

Conclusion

The client's clear vision proved helpful in realising the Te Rewa Rewa Bridge. An iconic bridge was required. Consultation with the client and *hapu* added to the knowledge of what emotions the bridge should engender. Site visits and historical research further enhanced this.

While I do not declare myself to be an artist, others refer to the bridge as a serious work of art. (6) From my perspective, I am pleased to think the bare structure 'tells the story' of the setting without adornment. Efforts to contextualise the bridge seem to have had a clear resonance with local community, and the bridge has become a potent cultural and community symbol.

Nervi, the great Italian engineer, talked of an authentic and truthful style where purity of line and shape, and absent of all decoration, gives immediate approval because they reflect nature. (7) I designed the superstructure elements to reflect an abstract form of nature that can be readily associated with the site. Making connections and relationships between the structural elements and the history associated with the site is the creative linkage.

While there is nothing truly original about the Te Rewa Rewa Bridge, the strong links between structure and nature possibly break new ground in bridge aesthetics. What we have is a perfectly functional bridge with no loading or vibration issues, which despite its modest size, magically enchants as a sculptural form seen in changing light.

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Postscript

In January 2011 artist Natalie Tate completed a commissioned landscape painting featuring Te Rewa Rewa Bridge. This is shown below. The Te Rewa Rewa *Pa* is shown historically on the left hand side, Te Rewa Rewa Bridge centre, and Mount Taranaki on the right hand side. A carved *waka* (canoe) prow is shown in the lower right corner. The *pa* buildings and the *waka* are to symbolise the site was once home to many who have now gone to eternal rest. The bridge and mountain lift the eyes skywards to recognise this.

On 28 March 2011 the Te Rewa Rewa Bridge was selected from a worldwide list of distinguished bridge projects to receive the 2011 Arthur G. Hayden Medal recognising single recent outstanding achievement in bridge engineering demonstrating innovation in special use bridges such a pedestrian, people mover, or non-traditional structures. The medal will be presented at the International Bridge Conference in Pittsburgh, Pennsylvania on 7 June 2011.

Later in 2011 the Te Rewa Rewa bridge won the 2011 Footbridge Award for the Technical Medium Span category in Poland.

In 2012 Natalie Tate completed a contemporary work featuring Te Rewa Rewa. This is shown above and features that designer and authors opening day speech written into this stunning work.

In 2014 local Taranaki artist Barbara Clegg completed an inspiring work entitled 'Te Wairua o Te Rewa Rewa'. This work captures many of the theological connections made by Te Rewa Rewa to its local topography.

An extract of the designers opening day speech follows:

'Many of us find natural spaces can take on the solemnity of a cathedral.

This site offers a rich assortment of theological themes that had influence on this bridge design.

The coastal horizon offers the tang of adventure. The sea whispers to us of longing and separation.

The beach signifies transition and change. The river sluices away all impurity,

Maunga Taranaki is a silent witness to what is eternal. The sky lifts the lid on life and allows us to dream without limits.

The wind is a metaphor for the wairua of the souls of Te Rewa Rewa that dwell here on this whenua. They are with us now.'

Peter Mulqueen, 5th June 2010.