Creating the Te Rewa Rewa Bridge, New Zealand

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Abstract

Te Rewa Rewa Bridge opened on the 5th of June 2010. In just over a year this unique bridge at the edge of the world in Taranaki, New Zealand, has won two international awards and has become a potent symbol for the community in which it is located. This paper dissects the thought processes of the bridge designer as an example to demonstrate how structural bridge elements can be contextualised to a bridge setting. This is in order for the bridge to be seen as a symbol with deep meaning to its local community, more than a purely functional bridge.

Keywords: iconic bridge design; structural form; construction method; contextual setting; analytical modelling; Te Rewa Bridge.

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

Introduction

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

Very little is written about the creative process as it pertains to bridge design. For a designer, it is essential to learn to dissect the thought processes needed to develop a design concept for any project in hand. The designing of the Te Rewa Rewa shared pathway bridge is a classical example.

The creative process for bridge design can be defined as being made up of three advancements. The first is transferring the designer's thoughts onto paper by making sketches. The second is from these sketches to construction drawings. The third advancement is from the drawing board to the wonder of a completed bridge. It is the first advancement that will be the focus of this paper.

During the first advancement, an engineer must hold multiple visions of the bridge in his mind's eye. These are sometimes described as "a fourfold vision of the project, simultaneously considering issues of structural form, mathematical analysis, construction methods, and the relationship of the structure to the site".[1] These have been renamed and reordered to reflect the experience of concept development in the Te Rewa Rewa Bridge. They are the 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 the span and deck alignment. Because a clear span of 70 m and a minimum deck soffit height of 4,5 m above normal water level were needed for the Te Rewa Rewa site, a single through-deck arch was chosen. 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 took into consideration the bridge site conditions, the contractor's experience, preferences, resources and facilities. With a very experienced oil and gas steelwork fabrication workshop just 1,5 km away from the Te Rewa Rewa site, a tied arch configuration was selected so that the superstructure could be fabricated in the workshop and transported to the 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 base footings were selected. Ready access to low cost volcanic (andesite) boulders from the contractor's own quarries provided the scour protecting riprap for both abutments.

Contextual vision is an acknowledgement that a bridge will be part of its environment and must add dignity to its setting. It can reveal to observers what its owners and designers had strived to create. This vision is used both to fine tune and to add something special to the two previous visions, and it is where the character of the bridge and its deeper meanings are truly expressed. The Te Rewa Rewa site clearly deserved an iconic bridge.[3] The word "icon"—in contrast to its modern meaning of simply being popular—in its true sense stands for a symbol that draws worshippers into a deeper reality. 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 the Ngati Tawhirikura *hapu* (the local sub-tribe), whose descendents were killed and are buried there. During the Musket Wars (1820–1830) and the Taranaki Wars (1860–1863) the site had been a battlefield and later was unjustly confiscated by the government. For most of the 20th century, it was used as a rifle range with limited public access, until reconciliation between the *iwi* and the government resulted in co-management by both *iwi* and the New Plymouth District Council. However, it was the poetry of James K. Baxter, arguably this country's greatest literary talent, which provided the true inspiration for the bridge design. As poet and contextual theologian, it was Baxter who put forth the thought to try and capture the essence of wind, with the idea of transformation as a metaphor for the spirit, or *wairua*, i.e. the souls of the dead. This led to the designing of 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 the complex and unique form of the bridge. It verifies the three previous visions and confirms that the development is structurally valid, with well-defined load paths that will result in a functional bridge.

Project Background

The history of a project must be known to fully understand its background. In October 2007, the New Plymouth District Council (NPDC) requested a registration of interest from the 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 away from the congested public road between New Plymouth and the suburb of the Bell Block (*Fig. 1*).

Three D&C consortiums were selected to tender. The two main weighted attributes for selection were price and design, each of which held 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 that had to be simultaneously beautiful and utilitarian.[3] The bridge was meant to be a delight to the eye and a token of respect for the descendents of the Ngati Tawhirikura buried there. The structure was to touch lightly on the Te Rewa Rewa side of the Waiwhakaiho River. The bridge was to blend well with the landscape as well as the social and cultural heritage of the ancient site.

Fig. 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 300 m from where it flows into the Tasman Sea

The bridge site stood 300 m upstream from the river mouth, and the bridge itself was to be 3 m wide between the 1200 mm high balustrades. It was to be a clear stretch across the river with a span of 70 m, and there were to be neither permanent nor temporary piers in the waterway, which stretched approximately 50 m wide at normal flow. The deck soffit was to stand a minimum of 4,5 m above normal river level, which meant that it should clear the surrounding flood plain for approximately 2 m. The bridge was to be designed in accordance with the loadings and codes referred to in the Transit New Zealand Bridge Manual[4] but in the event of emergency, it had to provide passage for a 3,5 t ambulance between New Plymouth and the 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 complete project. It was decided after the contract was awarded that the deck should be aligned with the summit of Mount Taranaki, which rises 2518 m high and dominates the Taranaki landscape (*Fig. 2*).

Concept Development

The Te Rewa Rewa Bridge concept needed the designer to keep in mind the fourfold final vision. Although the four visions were identified, detailed and divided into distinct categories for explanation purposes, in reality they had overlapping boundaries, particularly where structural form, construction method and contextual setting were concerned.

The bridge form, selected from the first three visions, proved to be highly asymmetrical and unique. In order to be priced competitively for the tender, it underwent deconstruction until it became a series of simple analytical models of 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 in the workshop, and then transport it as one large element to the site (*Fig. 3*). This lowered costs, ensured the fabrication was to the highest standard and meant there would be no need for site welds. All protective coating work could be completed in controlled conditions. The only bolted joints made on site were in the balustrades, which were fitted after the superstructure and the precast concrete deck panels were in place.

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 can be considered one combined vision. The structural form could be considered the "engineer's" vision and the contextual setting the "artist's" vision.

Vision 1—Structural Form

Given the 70 m 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 0,35 t/m^2. A truss superstructure would also require a similar quantity of steel. At an early stage of the design process,

Fig. 3: The Te Rewa Rewa Bridge superstructure being transported to site from the fabrication workshop. The superstructure as shown was approximately 85 m long and weighed 85 t. The journey distance was 1,5 km across mainly unpaved tracks and a golfcourse

initially, the truss option was considered as it had on-site assembly advantages over the arch. These advantages were however eliminated after it was decided to reduce costs through workshop fabrication and by transporting the superstructure as a single element to the site. A truss, by nature, has edges and angles that create disquiet and confusion to the 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 fairly recent reconciliation, a harmonious experience was preferred for the pedestrians as they crossed the bridge.

A cable stayed bridge configuration for a 70 m clear span would result in an estimated steel weight of 0,45 t/m^2.[2] The likely increased weight—and therefore, cost—over an arch bridge 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 British Standard; BS5400-2: 2006 Annex B provided a second reason to rule out this option. With very few cable bridges in New Zealand, and based on previous experience in designing cable structures, the cost of a cable bridge would be 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 foot 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. The site atmosphere gave the distinct feeling that the New Plymouth side of the bridge was the Pākehā (European descendent) side and that the Te 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 bridge a character opposite to what the client had requested.

Instead, an arch with a span-to-rise ratio of 10 was chosen. A low arch would also appear respectful and not dominate the low hills of the Pā (fortified village) site. Today, the arch frames the site as an 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 that the truss option was dismissed, a single, wide arch was selected. A large circular hollow core section (LCHS) was adopted to reduce arch fabrication cost. This can be curved by induction bending to form a parabolic profile. A faceted arch was avoided because the mitre joints would distract the observer. The range of LCHSs available gave sufficient scope to select a suitable diameter and vary the wall thickness according to demands.

The plane of the arch is vertical where it is most efficient. To complement the tubular arch, the deck structure was also kept tubular. 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 (*Fig. 4*). A tubular member was therefore used to trim each side of the deck structure. These members also provided a tie between the arch springing points.

The basic superstructure skeleton was therefore in 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 1,3 Hz in the torsional mode. The first horizontal and vertical modes surpassed the requirements of BS5400-2: 2006 Annex B.

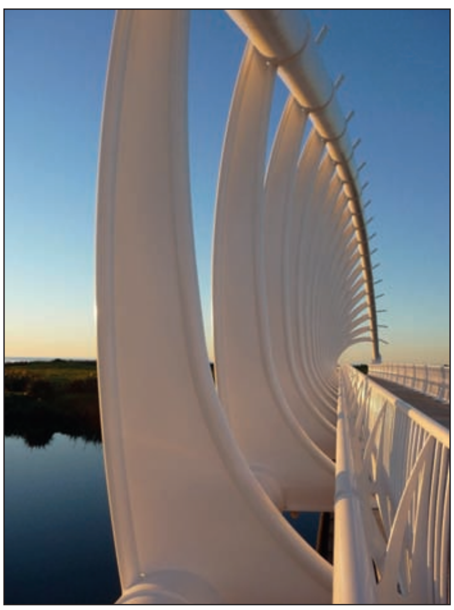

Fig. 4: An aspect of the Te Rewa Rewa Bridge showing the tubular arch forming a gateway. The horizon of the Tasman Sea coast is in the background

The deck material selected was to be 50 MPa concrete with 500 MPa reinforcement for durability and strength and 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 up to a considerable depth. Volcanic soils in New Zealand are infamous for large boulders which are difficult to pile if encountered. Heavy mass concrete abutments on large base slabs were used to provide adequate ground bearing, while base friction and lateral earth pressure from scour protecting riprap were selected to resist lateral actions.

The ground conditions provided extremely good bearing with only small amounts of settlement and abutment rotation possible. Over the 70 m span, the likely differential settlement between abutments would have only 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

For the arch superstructure to be transported to the site as one unit, it had to be a tied arch to prevent the springing points (ends) from spreading. With the site design requiring mass concrete abutments (see previous section) 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

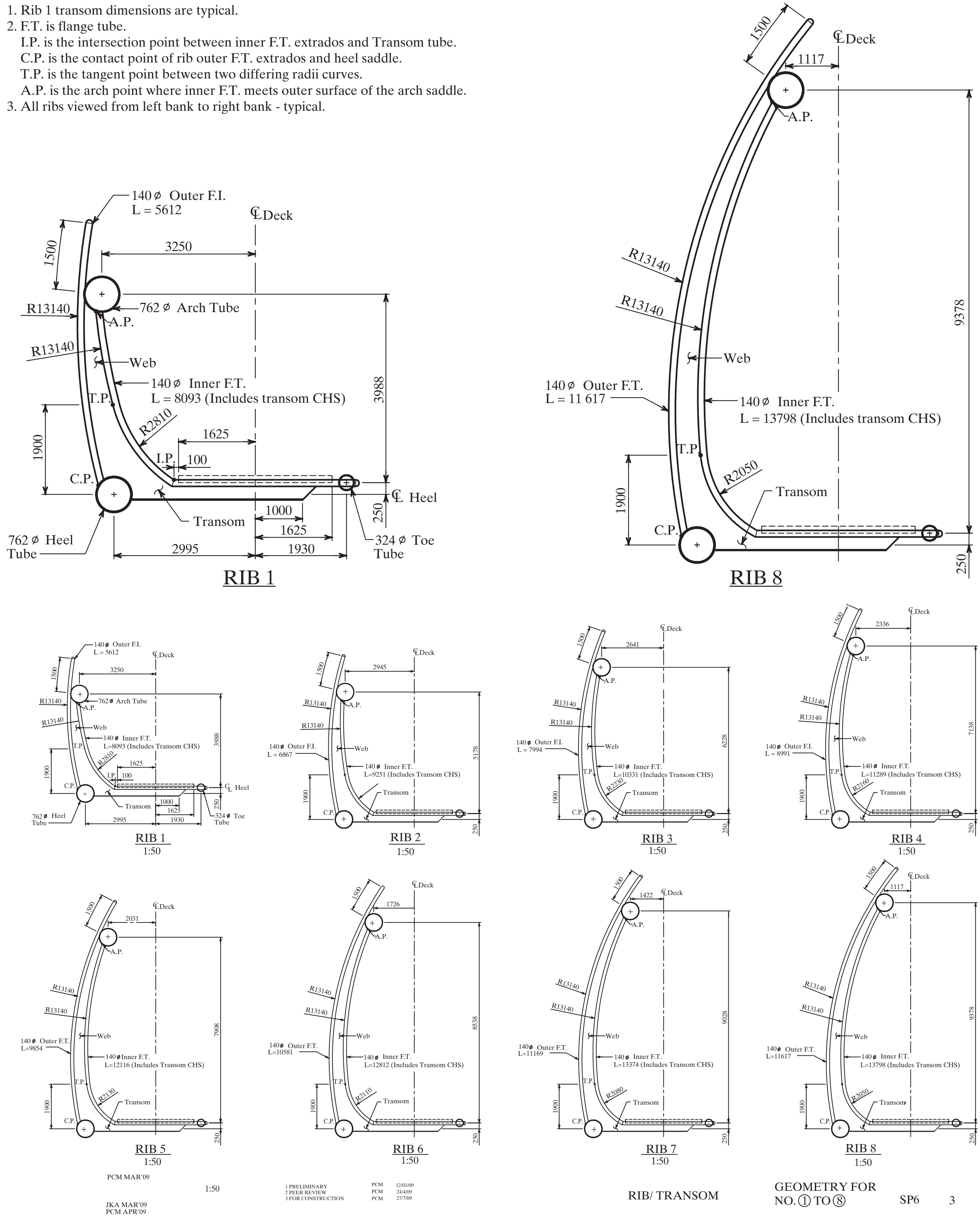

Fig. 5: Variability of ribs; defined forms are of the first and the eighth of the 19 ribs (units: mm)

steel springing would then be embedded in the concrete springing. (The true left steel springing can be seen on the right in *Fig. 3*.) To prevent distortion of the superstructure as a result of 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 the 19 evenly spaced cantilever beams (transoms) coincident with the ribs (*Fig. 5*). In order to utilise the diaphragm action of the panels for lateral stiffness, galvanised and waterproofed linage 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.

Vision 3—Contextual Setting

The single most important aspect of the bridge site was the fact that it gave access to the sacred land of 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 which has become significant for all M¯aoris of the Taranaki region. The Parihaka Movement embraced non-violent resistance to post-Taranaki War land confiscations by the government and was led by two Taranaki prophets, Te Whiti o Rongomai and Tohu Kakahi, 50 years before Mahatma Gandhi advocated non-violent resistance in India. During the 19-year period, from 1879 to 1898, Te Whiti, Tohu and their warriors were arrested and imprisoned without trial for various durations. The symbol of the movement, the *raukura* of three white *toroa* or albatross feathers, is still adopted today by the Māoris in the Taranaki district. It represents spirituality, the importance of making peace within and with others, and the necessity of maintaining goodwill despite conflict.

Not only was the bridge to invoke a sense of history and mystery, it was to engender a feeling of peace and harmony. A story about Michelangelo has been quoted from the 16th century, in which he reasons "bridges should be built as though they were cathedrals". This thought of Michelangelo reflects the 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 waharoa (gateway) was considered pertinent. Conscious not to mimic traditional Māori structures and risk offense, it was decided to skew the arch diagonally across the deck. This skewed arch formed 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 the 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, hangers were required. The most effective method was to use two planes of steel rod cross-bracing from the arch to each side of the deck. These provided efficient vertical and lateral restraint to the arch, prevented buckling in those planes and also provided 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 appearance and the feeling of peace and harmony.

Inspiration for the 19 curved ribs came from aspects of nature associated with the site and Baxter's poetry, which uses 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 *Figs. 1, 2* and *4*).

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 even distribution of stresses, both the arch and heel tubes 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 an extension 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.

An observer walks the bridge, and a poetic tension accentuates a 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, supporting the deck in a series of 19 cantilever beams terminating in the longitudinal toe tubes. The ribs and cantilever frames run parallel to the normal flow of the river and are at a 10% skew to the heel and toe tube alignment.

When on the deck, the skeletal structure of the bridge is quite open with little obstruction. Yet the ribs of the downstream side create a sense of shelter and 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 following 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 riprap. 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 as a result of temperature variation. (See *Fig. 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 the local people of Taranaki region.

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

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 that the overall concept is valid. A series of simple models was selected to understand the behaviour of the slender and asymmetric structure 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.

A classical arch theory was adopted to determine the axial loads in the arch tube and the 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 the 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, and were imposed on each of the abutments. Three components of the deck structure carried the counteracting tension between the 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.

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

Postscript

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 which recognises a single recent outstanding achievement in bridge engineering demonstrating innovation in special use bridges such a pedestrian, people mover, or non-traditional structures. The medal was presented at the International Bridge Conference in Pittsburgh, Pennsylvania on 7 June 2011.

On 5th July 2011, the bridge received the 2011 Footbridge Award for the medium span aesthetic category in Wroclaw, Poland.

Conclusion

The client's clear vision for an iconic bridge proved helpful in realising the Te Rewa Rewa Bridge. 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.

The bridge is referred to as a serious work of art by some observers.[6] The bare structure does "tell 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 absence of all decoration, gives immediate approval because they reflect nature.[7] The superstructure elements were designed 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 creative linkage at its best.

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

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SEI Data Block

Client:
New Plymouth District Council (NPDC)

Lead designer, bridge designer and design manager:
Peter Mulqueen of, Novare Design Ltd

Peer reviewer:
Peters and Cheung Ltd

Contractor
Whittaker Civil Engineering Ltd

Steel fabrication sub-contractor:
Fitzroy Heavy Engineering Group Ltd

Estimated cost: (USD million):	2,13
Service date:	June 2010