MOTT MACDONALD





# Okahu & Puhoi Viaducts Deck System Review

27 March 2020

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## Temporary Reinforcement Trusses

27 March 2020

# Issue and Revision Record

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# Contents

# Executive summary

Upon a request from Fletcher Acciona JV (FAJV) for Mott MacDonald New Zealand Limited (MM) to independently review a temporary works component associated with the deck construction for both the Okahu and Puhoi viaducts two potentially serious deck failure modes have been discovered. The temporary works concerned is critical for both modes of failure.

These deck failure modes have been identified by calculation and assessment. MM first notified FAJV of these failure modes on 6 March 2020 by email.

One failure mode is associated with the sudden buckling failure of the TRTs cast into the precast deck panels during construction of the deck. The other failure mode is associated with the fatigue fracturing of the TRTs embedded into the permanent viaduct deck leading to an accelerated decline in deck durability during its service life.

**Buckling Failure Mode – Temporary Works**

This failure mode eventuates from a TRT top chord buckling failure. This can potentially occur either in preparation for or during the topping pour. Over the two viaducts there are some 17,400m$^2$ of precast deck panels that are potentially prone to this collapse mode. In our opinion, sudden failure of a top chord is possible and the consequence is considered to be extreme; therefore this is deemed to be a critical risk. It is recommended that the temporary works designer verify the resilience of the TRT during manufacture and construction and demonstrate adequate margins of safety in the design before proceeding further with the viaduct deck construction. This should include full scale loading to failure of representative pre-cast panels.

**Durability Failure – Permanent Works**

The second failure mode comes about from the potential sudden changes in deck stiffness caused by fatigue fracture of the TRTs cast into the permanent deck slabs.. The consequence of this mode is reduced service life for the deck. It is recommended that the bridge designer reviews their design and verifies that this potential failure mechanism has been addressed.

# 1 Background

## 1.1 General

FAJV commissioned MM to review the TRT design. MM understands there was a request from the FAJV designers ("Beca") that the TRTs should be further reviewed following the required approval by the Temporary Works Engineer ("TWE"). The TWE is Acciona Ingerieria ("A-ING"). They are a Spanish subsidiary of Acciona Infrastructures ("A-INFRA") – one of the Design and Construction Joint Venture partners ("D&C JV") that make up FAJV.

This report is confidential and is prepared for FAJV. The contents of this report may not be used for any other purpose other than in accordance with the stated purpose, nor may this report be relied on by any other party.

The purpose of this report is to highlight to FAJV the serious concerns held by MM with respect to the design of the TRTs and their role in the overall viaduct deck system. The permanent deck and superstructure design have not been considered as part of this review except as they pertain to the TRTs.

## 1.2 Review Inputs

The construction drawings numbered P2Wk-DRG-SE-19-0107 Rev 1 and P2Wk-DRG-SE-18-0107 Rev 1, for the Okahu and Puhoi viaducts respectively, and both dated 27 September 2018, called for the TWE to 'satisfy themselves' that the TRTs are adequate for the temporary state when the 185mm (for Okahu viaduct) or 205mm (for Puhoi viaduct) thick topping concrete is poured onto the precast deck panels.

The precast panels are intended to span transversely across the 4 girder lines of each viaduct. The girders are numbered 1 to 4 from one side to the other. The typical 'outer' precast panels are 130mm thick and supported on girders 1 and 2, and 3 and 4, and include a cantilevered portion of deck beyond girders 1 and 4. The typical 'centre' panel is also 130mm thick simply supported between girders 2 and 3.

All precast panels are stiffened with TRTs at 300mm centres across the 2.7m panel width. Each TRT has a single HD20 rebar top chord and two HD20 rebar bottom chords. The vertical centroid distance between top and bottom chords is 154mm for the Okahu viaduct and 174mm for the Puhoi viaduct. The chords are held apart by diagonal HD10 bent 'zig-zag' diagonals which have 4mm fillet welds at 200mm centres on the outside and inside bend to the chords. Typical TRTs are shown in **Photo 1.**

**Photo 1:** Typical Temporary Reinforcement Trusses (TRT)

MM understands only the precast panels for the Okahu viaduct have been cast to date. These have been cast at Wilsons Precast, Heritage Way, Otara, Auckland. **Photo 2** and **Photo 3** below show some of these panels and these photos were taken on 12 March 2020.

A-ING carried out detailed design and a supplementary annex for the design of the TRTs cast into precast deck panels as ‘strong backs’. The design report is dated February 2018 and the Annex (for shear capacity improvements of the TRTs) is dated February 2020. The Annex is further supplemented by a description of the weld procedure specifications (“WPS”) but this is not dated as such. The actual WPS is dated 29 September 2017 and the reinforcement bar mechanical testing is dated 11 October 2018.

**Photo 2:** Typical centre precast deck panels

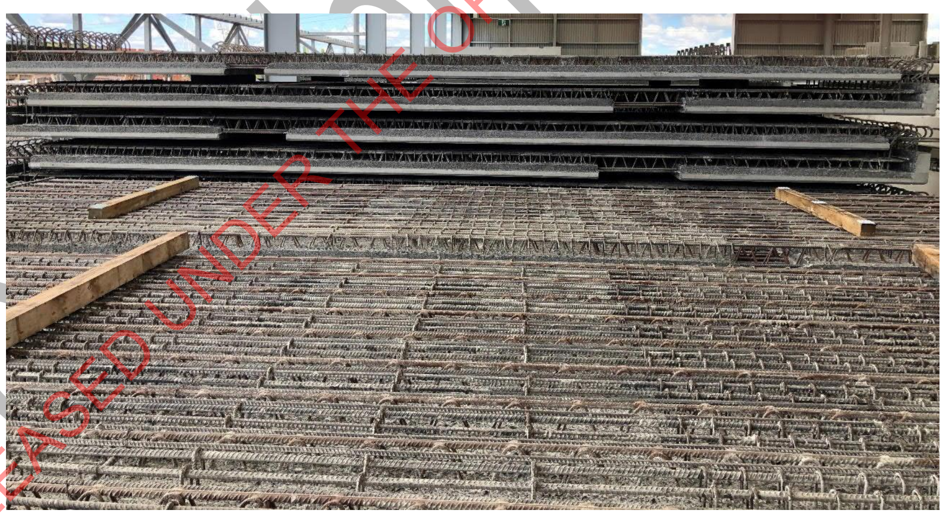

**Photo 3:** Typical outer precast deck panels

MM understands that the precast panels cast to date have been made to the A-ING construction issue drawings (No. 1 to 7) dated 10 February 2020.

As clearly stated in the construction drawings numbered P2Wk-DRG-SE-19-0107 Rev. 1 and P2Wk-DRG-SE-18-0107 Rev. 1, the TRTs are to remain within the permanent deck and to become 'redundant' during service loading. Due to their welded fabrication they are expected to suffer from fatigue fractures through the chords and diagonals.

## 1.3 Examples of Similar Bridge Deck System

FAJV has supplied MM with a briefing paper generally outlining bridge deck systems similar to that described in the construction drawings. They include the Omnia Bridge deck system and five other bridge examples plus load testing outlining of a 6th bridge. The Omnia bridge system is used up to 3.7m spans with the planks most often in the longitudinal orientation; this is to reduce the number of potential fatigue cycles. The planks are only a single truss wide to prevent the risk of progressive collapse. Omnia alert contractor's attention to prevent damage to top chords by lifting only at points of top chord restraint; this is to reduce the risk of top chord buckling.

The other bridge deck examples shown have spans of an estimated 4m plus a 2m relieving cantilever on each end; 2.45m simply supported; 2m continuously supported; 3.0m and 2.0m plus 1.5m relieving cantilever; and 2.2m simply supported. The load tested panels are most greatly loaded on the relieving cantilever; this reduces the adjacent maximum simply supported moment by at least half the cantilever moment. Generally, the examples shown have much smaller spans to that proposed for the Okahu and Puhoi viaduct precast panels. The top chord compression is in proportion to the square of the span divided by the depth of the TRT. A pure simply supported precast deck panel of a particular span length will have larger TRT top chord compressive stresses than when compared to the same span but with the TRT also supporting a cantilever.

# 2 Concerns with the Precast Deck System

MM wish to outline two serious concerns associated with the TRTs as integral components with the total viaduct deck system as follows:

1. The potential for sudden failure of the TRTs during deck construction resulting in the collapse of precast deck panels,
2. The durability failure of the permanent deck during service life caused by the effects of the fatigue fractured TRTs.

The first is of highest priority as it is a potential safety issue.

These failure mode concerns are further described in detail in Sections 3.1 and 3.2 below.

# 3 Failure Modes

## 3.1 Sudden Top Chord Buckling Failure of TRT during Construction

### 3.1.1 Description

The centre precast panels span between the top flange outstands of girders 2 and 3 of the viaducts. The Okahu centre panels span 6.25m and the Puhoi Viaduct centre panels span 6.95m. The model for analysis is a simply supported span. Each 2.7m wide panel has 9 No. TRTs at 300mm centres providing the flexural support ('strong backs') to carry the panel self-weight; construction loading during the topping pour preparation; and the wet concrete topping pour.

These loads are resisted by the TRTs in flexure which is maximum at midspan and by shear which is maximum at the main girder supports. The TRT top chords are in compression and bottom chords are in tension. There is additional permanent reinforcement within the 130mm thick precast slabs that also contribute to the tension action of the moment resisting couple within the span. The tension capacity of the precast slab has been ignored because it yields suddenly whereas the reinforcement is expected to elongate and yield in a ductile manner prior to failure.

When the TRT top chord compression stresses are sufficiently high, the HD20 top chord could buckle suddenly. This results in a sudden loss of the moment resisting couple that was provided by the statically determinate TRTs. The TRTs have no redundant load paths. The top chord buckling capacity is governed largely by its slenderness ratio. The slenderness ratio is the top chord effective length over its radius of gyration; which for a 20mm diameter bar is 5mm.

Selecting the top chord effective length requires both guidance from codes and engineering judgement from the designer. For example, the unconservative selection of 'fixed – fixed' end restraints will give an unconservative top chord buckling capacity. The assumed end fixity will also attract additional bending stresses within the top chord due to possible misalignments between restraints or damage (cranks or kinks) within the chords.

The damage may come about due to the precast panel construction process or preparation of the topping pour when the top permanent reinforcing is placed. Allowance for some degree of top chord misalignment or damage is considered prudent when using a fixed – fixed model. MM calculations show the top chords are vulnerable to sudden buckling with just a 2mm misalignment between restraints 200mm apart or a 2mm kink within the top chord. The combination of axial and bending stresses reduces the unconservativeness associated with the fixed-fixed model.

A reasonable selection of 'pinned-pinned' end restraints more accurately accounts for the fact that the top chord acts as a series of 200mm long chords. It is slightly conservative in that it assumes the restraints have negligible torsional restraint. MM calculations show all panels for both the Okahu and Puhoi viaducts will be loaded beyond typical safety margins used to prevent top chord buckling during the topping pour. As with the fixed – fixed model the top chords are vulnerable to damage which introduce P-delta effects and dramatically reduce buckling capacity compared to an ideal straight chord.

We have considered the unlikely situation of a missing restraint and therefore an effective length of 400mm. This indicated the TRT top chord would buckle for all precast panels of both the Okahu and Puhoi viaducts during the topping pour.

There are about 6,500 TRT top chord compression regions in the Okahu and Puhoi viaducts with a combined area of precast panels exceeding 17,400m$^2$. It is likely that at least some chords will be damaged as described above leading to a sudden top chord buckling. This mode could lead to progressive collapse of any 2.7m wide panel. Progressive collapse occurs as any buckled top chord quickly sheds its lost axial capacity to the TRT top chords immediately adjacent thus overloading them leading to their buckling.

The possible failure combined with the extreme consequence of failure, which is multiple fatalities, represents a critical risk which must be fully addressed before further construction of the design deck system proceeds.

Additionally, the precast panels appear not to have been cambered and are flat. This can be seen in **Photo 2** and **Photo 3** above. MM calculate by simple elastic theory that the Okahu centre panel have midspan deflections of over 30mm occurring during the topping pour. This will cause 'ponding' of the topping concrete and exacerbate both the deflections and the compression of the TRT top chords.

### 3.1.2 Panel Load Testing

MM has received load testing results for a centre and an outer precast panel of the Okahu viaduct. The load tests were required by drawing P2Wk-DRG-SE-19-0107 Rev. 1. MM has reviewed a package consisting of load test planning documents, emailed results, and photographs for the load testing carried out on the 23 and 27 August 2019. Kentledge for the tests comprised precast segment stacking cradles of 4.0t weight and filled TrafFix Water-Wall barriers each of 0.5t weight. Refer to **Photo 4** showing load testing of an Okahu centre panel.


**Photo 4:** This shows load testing of an Okahu centre panel

Generally, the measured deflections were slightly less than half that expected by elastic theory. This suggests that the plywood sheets placed directly onto the TRT top chords were clamped to the top chords by the kentledge during load testing and formed a rudimentary but effective composite top flange to stiffen the precast panel; this resulted in abnormally low deflections but also possibly prevented top chord buckling. It is suggested if further load testing is carried out on the precast deck panels, then the kentledge is completely separated from the TRT top chords, and it is placed such that no possible 'running' or longitudinal shear connection exists between the TRTs or precast panel and the kentledge. The precast panels should also be tested to failure so that the failure mode may be recorded.

Some precast panels should be load tested with deliberately damaged (kinked) or misaligned TRT top chords to demonstrate a likely scenario. The outer panels should be loaded first between the supports, and only then on the cantilever as this loading reduces compression in the TRT top chords spanning between the supports.

## 3.2 Durability Failure during Service Loading

According to construction drawings numbered P2Wk-DRG-SE-19-0107 Rev. 1 Note 3 and P2Wk-DRG-SE-18-0107 Rev. 1, Beca consider the TRTs are to become redundant due to fatigue considerations. MM agree with this and estimate fatigue fracturing of the TRTs will be within 1 year of opening to traffic. This is based on an assumed fatigue detail classification (which considers the weld embrittlement, eccentricity of between the chord and diagonal creating an abrupt stress riser) and an estimated number of load cycles.

The chord stresses due to the cyclic live loads can be compared to the allowable fatigue stress range calculated from the assumed fatigue detail classification and estimated load cycles. The actual stress range within the chords is greater than the allowable fatigue stress range after just one year of traffic.

Fatigue fracturing of the TRTs is most likely to occur first at points of high bending moment; that is in the top chords over the girders and in the bottom chords between the girders where stress ranges are greatest. The initial stiffness of these relatively thin decks is governed by the unfractured TRTs and the permanent reinforcement. **Photo 5**. shows the extent of reinforcement within the deck panels made up with the TRTs (shown rusted) and the permanent reinforcement (shown grey). At points of TRT chord fracture there will be points of sudden change in deck stiffness.

Change of stiffness due to the TRT fatigue fracture will result in sharper curvatures in the deck compared to the deck sections further away from the change in stiffness. By linear elastic beam theory, the inverse of radius of curvature is equal to the inverse of the second moment of area of effective reinforcement, for any applied constant moment and material elastic modulus.

The permanent deck is therefore expected to behave like a series of stiffer links connected by less stiff connections at points where bending moment is highest. The higher strains associated with the sharper deck curvature will cause cracking in the deck cover concrete. That is to top cover concrete above the girders and the bottom cover concrete between the girders.

**Photo 5:** Deck panel in the process of being tied and

Further cyclic traffic loading will also result in the fractured TRT chords ‘working’ within the deck creating cavities for moisture to collect. This could cause premature corrosion of all the reinforcement within the deck close to these locations.

# 4 Conclusions

MM were engaged by FAJV to provide an independent review of the TRTs after they had some shear capacity improvement works carried out on them. Until then A-ING of Spain, as the TWE, had approved them.

MM undertook a first principles analysis of the TRTs and their functional roles within the total viaduct deck system.

From investigation of the viaduct construction drawings the dual roles of the TRTs are:

- To act as 'strong backs' to allow the thin precast panels to span over and cantilever beyond the 4 girder lines without temporary works;
- To become redundant within the thicker permanent viaduct deck system.

MM understand through this independent review that the TRTs perform a limiting or critical role in the deck system during construction and in service.

MM concludes the TRTs are critical to two possible failure modes; one potentially sudden during construction and the other resulting in the accelerated decline of deck durability.

# 5 Recommendations

MM recommends the following actions for FAJV to undertake in regard to the Okahu and Puhoi Viaduct deck system:

Temporary Works

1. Request A-ING as TWE to re-calculate the TRT top chord buckling capacity and margins of safety during the work associated with preparing for the topping pour and pouring the topping. The critical risk of a sudden precast deck failure demands appropriate margins of safety. It is recommended that some top chord damage is considered in determining buckling capacity.
2. Conduct further load testing of the already cast Okahu viaduct precast deck panels. Ensure the panels are accurately supported to mimic loading of the topping pour as accurately as possible. Ensure kentledge offers no lateral restraint to the TRT top chords or provides any top flange effect to moreclosely represent the wet concrete loading. Panels should be tested with undamaged TRT top chords and with deliberately damaged or misaligned TRT top chords. Test to failure and note the failure mode. Place kentledge only between the lines of support first; not on the cantilever portion of the outer panels. Record loading and deflections accurately then assess the results against first principle analysis.
3. That the bridge designer reviews their design to consider the effect of incorporating the TRTs into the permanent deck. This should include the potential fatigue failure mechanism identified in Section 3 in relation to long term deck performance and durability.

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