COI-2 Structural Engineering Expert Report

MTRCL Shatin to Central Link Contract 1112

by

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My Experience as a Structural Engineer

1. I am the Managing Director and Chairman of James Lau & Associates Limited. My experience as structural engineer has been set out in detail in paragraphs 1-11 of my expert report for the issues in the Original Inquiry dated 10 December 2019 **("my COI-1 Report")**. For ease of reference and the avoidance of repetition, the relevant parts of my COI-1 Report are extracted and reproduced as **Appendix JL2-A**.

2. Apart from the Original Inquiry, I am also appointed as an expert in structural engineering for the Government for the Extended Inquiry. I fully understand that I have a paramount duty to the Commission of Inquiry **("COI")**. I understand that I have a duty to be truthful, independent and impartial.

The Verification Report

3. In April 2018, MTRCL complained that the Contractor, Leighton, did not submit the required "Request for Inspection and Survey Check Forms" **("RISCFs")** for structural works of the North Approach Tunnels **("NAT")**, the South Approach Tunnels **("SAT")** and Hung Hom Stabling Sidings **("HHS")**.

4. The RISCFs were required to be properly prepared and documented during the execution of the structural works.

5. On 20 December 2018, MTRCL further informed the Highways Department that, in addition to the lack of RISCFs, there were also insufficient construction records of coupler installations. There were issues of change of steel reinforcement lapped bars to coupler connections and insufficient materials testing for the NAT structures. Subsequently similar situations at the SAT and HHS were also identified.

6. On 15 May 2019, MTRCL submitted a "Verification Proposal of As-constructed conditions of the NAT, SAT and HHS" **("Verification Proposal") [BB8/5126-5145]** to verify the as-constructed works, to ascertain the structural integrity and to ensure the quality of the structures in NAT, SAT and HHS. The Verification Proposal was accepted by the Government.

7. The Verification Proposal contained two parts. Part 1 was further subdivided into two sub-parts – Part 1a and 1b. Part 1a of the Verification Proposal involves consolidating and verifying the available construction records with a view to identifying any gaps in site inspection records, material testing records and design changes records. The work under Part 1b covered reviewing and ascertaining the as-constructed conditions of the works, including design changes made as well as the quality and workmanship of the structures so as to close the gaps identified in Part 1a. It then determined that the gaps identified needed to be followed up with a structural review under Part 2 of the Verification Proposal.

8. Pursuant to Part 2 of the Verification Proposal, MTRCL conducted a structural review and devised schematic suitable measures to address the deficiencies identified. In so doing, as part of the required suitable measures, MTRCL also proposed to develop a long term monitoring scheme to monitor the structural performance of the as-constructed NAT, SAT and HHS structures. For the purpose of this exercise, MTRCL engaged Atkins and AECOM as the Detailed Design Consultants **("DDC")** to perform the structural review.

9. After the structural review, MTRCL produced a Verification Study Report **("Verification Report") [BB16/9952-10000]** to present all the findings and results. The results of the structural review are set out in Part 2 of the Verification Report.

10. I was aware of the methodology adopted and the rationale behind the investigation and structural review carried out by MTRCL's DDC for the purpose of the Verification Report. I was also provided the Updated Design and the detailed designs of suitable measures proposed by the DDC. To comply with COI's directions, I applied engineering principles in reviewing or considering the Verification Report, the Updated Design and the designs of the suitable measures proposed. I would look at the Updated Design from the point of view of structural safety and consider whether the as-built structures are fit for purpose. For structural elements that were found to be overstressed, I would study the designs of suitable measures for the overstressed elements. I would also provide my comments on Mr. Nick Southward's structural engineering expert report for the Extended Inquiry dated 18 October 2019 **("Mr. Southward's COI-2 report") [ER(COI2)1/items 10.1-10.6]**.

Part 1 - Irregularities found in the Review

11. Under Part 1a of the investigation, MTRCL's DDC consolidated and verified all construction records that were made available to them. A summary of the available RISCFs is shown in Table 1 of the Verification Report **[BB16/9963]**. The percentage of unavailable RISCFs for NAT, SAT and HHS ranges from 39% to 78%.

12. The following further irregularities were also found:

    (1) According to the record in the RISCFs, the coupler installation work at the Variable Refrigerant Volume Plant Room **("VRV Room")** was rejected by MTRCL at hold point inspection, yet Leighton proceeded with the concreting work without permission. The work was not accepted by MTRCL and Leighton would have to rectify the work.

    (2) Water seepage was discovered at three stitch joints at NAT. Subsequent investigation found defective coupler connections at the said stitch joints. It has now been discovered that no RISCF was submitted by Leighton during the construction of the stitch joints in question. The three defective stitch joints were subsequently rectified by Leighton.

    (3) At the Shunt Neck, defective coupler connections were also found and remedial works have to be carried out by Leighton.

    (4) On rebar testing, it was found that about 7% of the rebars delivered to the site under Contract 1112 was not sampled for testing as per the applicable requirements.

    (5) On design changes, it was found that couplers had been used at some of the construction joints in lieu of lapped bars which were specified in the original accepted design. This was a deviation from the original design.

    (6) At the connection between the diaphragm wall and NSL track slab of SAT, drilled-in bars were used at some locations instead of Type 2 couplers which were specified in the accepted design. This was again a deviation from the original design. Further, the required pulled-out test records for the drilled-in bars in question were not available.

(7) A number of non-destructive tests and concrete core tests were carried out under the Verification Proposal. On cover-meter scanning, it was found that 9% of the scanned area had insufficient concrete cover.

13. Following Part 1b investigation, a summary of findings and recommendations is provided in Table 5 of the Verification Report. The table contains the following recommendations:

(1) Because of the lack of testing of about 7% of the rebars used, 4% reduction in strength should be applied to rebars with a diameter equal to or greater than 16mm, and a 13% reduction in strength for rebars with diameter of 12mm and below.

(2) For the 9% of the scanned area that showed insufficient concrete cover, fire proof coating and concrete thickening are to be carried out.

(3) To account for the possible defective coupler connections in the works, on the basis of a 35% defective rate discovered in the Hung Hom Station Extension structure, a 35% strength reduction factor is to be adopted for the structural assessment of the structures in NAT, SAT and HHS.

(4) Because of the unavailability of pull-out test records, the contribution of the drilled-in bars is to be ignored in the structural assessment.

14. Although no investigation was carried out by MTRCL to the coupler connections used in NAT, SAT and HHS, it is my understanding that MTRCL considered that to account for the issues of workmanship identified, it was prudent to apply a strength reduction factor in areas where coupler connections have been used to replace lapped bars. In the absence of any other evidence or data, a strength reduction factor of 35% has been adopted. This defective rate used is comparable to the strength reduction factor used at the NSL platform slab in the adjacent Hung Hom Station Extension. This area is adjacent to the NSL tunnel at SAT. For other structures in NAT, SAT and HHS, the same factor is applied although the construction work was easier than that of the NSL tunnel at SAT.

My opinion on the adoption of the 35% defective rate of couplers

15. I have looked at the photos of the exposed original internal stitch joints at NAT (i.e. the stitch joint within Contract 1112) **[BB7/5112-5115]** (where there was no mismatch of materials) and VRV room **[BB8/5790-5793]**. The photos show unexpectedly poor workmanship in the coupler connections. The said defects in the stitch joints at NAT would not have been discovered had there not been water leakage through the joints. In view of that, I am of the opinion that a strength reduction factor must be applied to account for the possible defective coupler connections in the structure. As to what percentage of strength reduction factor is appropriate, the only reference currently available is the 35% defective rate which was determined by way of statistical analysis on the basis of the opening up results in relation to the platform slabs and diaphragm walls under the Final Report on Holistic Assessment Strategy for the Hung Hom Station Extension **[OU5/3229-3350]**.

Part 2 - structural review

16. Upon review of the as-built structures, DDC found that when the structures are checked (which is a Section Check as defined in paragraph 26(b) of my COI-1 Report) on the basis of the design parameters used in the Original Design, some locations of the structure were found to be overstressed and suitable measures would be required to be implemented. MTRCL and its DDC then carried out another review by reference to a new set of design parameters, which is referred to in the Verification Report as the Updated Design. Based on the Updated Design, the number of localised areas with overstressing was reduced. The extent of suitable measures required was also reduced. I was given a set of the Updated Design for my reference. I agree with the structural review done by the DDC and the recommendations made based on engineering principle and from the point of view of safety and fit for purpose. In particular, I agree with the set of principles adopted by the DCC in their design check. I have set out my opinion in great detail in paragraphs 24-43 of my COI-1 Report as to what factors are to be considered in deciding whether a structure is "safe" and "fit for purpose", which is reproduced in **Appendix JL2-A**. I do not repeat them here. In my opinion, similar principles and considerations should be applied for the works in NAT, SAT and HHS.

17. Part 2 structural review involved a comparison between the spare structural capacity of the structural elements and the extent of strength reduction required due to defective coupler installations and lack of rebar testing. Suitable measures are recommended if the spare structural capacity (in terms of percentage) is less than the required strength reduction percentage. Here suitable measures include structural modifications, remedial works, long term monitoring scheme and the imposition of constraints on potential future modifications to the structure and its use.

18. In the structural assessment, MTRCL's DDC allowed the provisions/flexibilities in the Original Design to be reviewed and rationalized and produced the Updated Design. In the Updated Design, there are 3 items for NAT (Appendix B1 of Verification Report) **[BB16/9990]**; 7 items for SAT (Appendix B2 of Verification Report) **[BB16/9992]**) and 2 items for HHS (Appendix B3 of Verification Report) **[BB16/9995]**).

19. Based on my Stability Check (as defined in paragraph 26(a) of my COI-1 Report), save for the trough walls, it is my opinion that the other structures in NAT, SAT and HHS do not have any issue of stability. Under the Stability Check, some of the trough walls in HHS cannot safely resist the horizontal impact load from a derailed train. I shall discuss the design check of the trough walls in subsequent paragraphs of this report. However, some of the structures are also overstressed in some areas, for example the NSL slab at SAT **[Appendix JL2-B],** and failed to satisfy the Section Check and the fit for purpose requirements. Therefore, there is a need for the implementation of suitable measures under the Section Check.

20. I have to mention that although no opening up was carried out by MTRCL, other types of investigation works were carried out by MTRCL. For example, cover-meter scannings were conducted to check the thickness of concrete covers and the reinforcement spacing at various locations and defects were found.

21. Insufficient concrete cover has an impact on the fire resistance and durability of the structures, both relating to the requirements for fitness for purpose. To remedy such defect, fire proof coating and concrete thickening should be applied at localised areas with insufficient concrete covers.

22. The proposed scheme of suitable measures is given in Appendix C of the Verification Report **[BB16/9996-10000]**. I was provided with a set of the detailed

design of the suitable measures required. The design of the suitable measures has recently been accepted by the Government. I understand that works on the suitable measures are being implemented on site.

Mr. Southward's COI-2 report

23. I was given a copy of Mr. Southward's COI-2 report. I have read his report and have the following comments.

Section 4:- Coupler connections/coupler/coupler engagement

24. One of Mr. Southward's criticisms in his COI-2 report is that there was no opening up of the structure by MTRCL to identify defects in the structure and yet the same defective rate (35%) for the coupler connections in the station structure was used by MTRCL's DDC in the design checks for the works in NAT, SAT and HHS.

25. As I understand it, this was a decision taken by MTRCL at the time not to carry out further opening up work at NAT, SAT and HHS.

26. Despite the fact that there was no opening up of the structure for investigation, I considered that it was reasonable and in fact prudent to apply a strength reduction factor in areas where coupler connections have replaced lapped bars on account of the uncertainty in workmanship. The 35% defective rate used is comparable to the strength reduction factor used at the NSL platform slab in the adjacent Hung Hom Station Extension. The NSL tunnel of SAT is adjacent to the NSL platform slab, and the steel fixing work for SAT was done by the same steel fixer, Fang Sheung **[FF1/13 §3]**. It is therefore reasonable to adopt a similar defective rate for the coupler connections in SAT. For the other structures of NAT and HHS, the same factor of 35% was also applied by MTRCL. The photos of the exposed original stitch joints **[DD14/15340-15364]** and VRV Room **[BB8/5790-5793]** show unexpectedly poor workmanship of coupler connections. The said defects in the stitch joints of NAT were discovered because of water leakage through the joints. In my opinion, although the steel fixing works for NAT and HHS were done by a different steel fixer, the works were however supervised by the same main contractor and MTRCL, the 35% reduction rate (being the only reference at this stage) adopted in the design check is reasonable and appropriate. I come to this view because of the poor coupler connections at the VRV Room, the original

internal stitch joints at NAT (i.e. stitch joint within Contract 1112), and the Shunt Neck, and there is nothing to suggest that the quality of the other coupler connections in HHS (in particular the deviated works) would be of better quality.

27. Mr. Southward carried out his own analyses of the structure using his revised defective rates for the couplers and shear links. He suggests that based on his findings, no suitable measures are required.

28. I do not agree with the defective rates Mr. Southward used in his analysis. In his calculation of defective rates, he used Dr. Wells' analysis which according to Professor Yin is incorrect. I do not agree to account for the contribution of partially engaged coupler connections in structural assessment. As I have stated in my COI-1 Report at paragraph 56:-

> *"I was provided with a total of 7 samples of the BOSA coupler assemblies for my inspection. I studied and tested the coupler assembly. To produce the butt-to-butt condition, I tightened the assembly by hand. Upon tightening, I could not cause any noticeable movement between the threaded bar and the coupler by pulling i.e. it was locked. However, when I allowed the samples to be partially engaged with different number of threads, I could always cause relative movements between the threaded bar and the coupler simply by pulling the assembly by hand. These are out-of-slip movements at the coupler connection because of partial engagements. Such relative movement is noticeable. These out-of-slip movements would be in addition to the permanent elongations manifested by the coupler assembly when it is stressed under loading. This can be a problem if the partially engaged couplers are used and embedded in concrete structure. According to the results of the tests commissioned by MTRCL, the permanent elongation of the partially engaged coupler connections could be up to 0.51mm **[OW1/240]**. Adding the said permanent elongation to the out-of-slip movement, the total deformation of the coupler connection would be a lot more than the 0.3mm maximum crack width allowed by the Concrete Code under the serviceability limit state **[H8/2928]**. Hence partially engaged coupler connection with a possible total deformation of more than 0.51 mm is unacceptable. I therefore have no confidence in the coupler assembly if it is only partially engaged. It is also difficult to come up with reliable methods to meaningfully calculate and ascertain crack widths or deflections in the*

structural element if the reinforcements are connected by partially engaged couplers."

29. According to the small number of laboratory tests commissioned by MTRCL **[OW1/93-108,239-268]**, nearly all partially engaged couplers failed the permanent elongation test, a violation of the manufacturer's recommendation and clause 3.2.8.2 of the Concrete Code. These partially engaged couplers failed the "safe" and "fit for purpose" test.

30. Mr. Southward does not provide any design checks on deflections, durability and crack widths in his COI-1 or COI-2 reports. In the circumstances, the partially engaged couplers should not be accounted for in assessing whether the structure is safe and fit for purpose.

Section 4:- Trough walls

31. According to MTRCL's DDC, the trough walls at HHS failed to satisfy the Section Check at their base. Because of the structural layout, the walls in question are cantilever structures. Rupture of the section at the base may lead to collapse of the trough walls, thus giving rise to stability problems. The trough walls were designed to take collision loads in the event of train derailment. Mr. Southward produces an alternative design check by yield line analysis for the trough walls at HHS. He found that even with a strength reduction of ***35%*** due to defective couplers, the trough walls are still safe.

32. In my opinion, there is a need for the suitable measures proposed by MTRCL's DDC. Suitable measures at some of the trough walls are meant to protect the columns that support the building above from possible damage caused by derailment of trains. It is important that these columns should not be affected in the event that a train accidentally hits and damages the trough walls in front of the columns. It is important that the trough walls do have adequate factors of safety against overstressing, local failure, excessive deflections or collapse of the wall when they are hit. To ensure structural integrity, suitable measures in the form of wall thickening and additional horizontal concrete struts are required for the trough walls near the movement joints where there is concern for defective coupler connection.

33. Mr. Southward said that typically, the approach adopted by AECOM in its calculation is that when the impact load hits the wall, it is spread longitudinally on both sides of the impact point and the strength of the wall is mobilised in both directions. He said that the method used by AECOM to analyse the effect of the train collision load is conservative. AECOM has designed on the basis that the wall is vertically spanning as a cantilever and that the length of wall mobilised to resist the train impact force increases at an angle of 45 degrees down the wall. The impact load from a derailed train is one of the ultimate load cases. The use of a simplified elastic analysis by AECOM to assess the effects of an ultimate load, although perfectly valid and accepted for use in design codes, is not the most accurate method. Mr. Southward therefore adopts yield line analysis to make an assessment of the capacity of the trough wall upstands in resisting such impact load. Mr. Southward's yield line analysis of the trough walls showed that the as constructed trough walls, even with a strength reduction factor of 35%, can withstand the train collision loads and are therefore safe.

34. My comment is that AECOM analysed the trough walls based on 35% defective rate of couplers and 45 degree spread of load. AECOM's method is an elastic method which is commonly adopted in the industry and is widely accepted by structural engineers. The results of the analysis indicated that suitable measures are required to be implemented. Yield line method is a kind of plastic analysis. Although the use of plastic analysis and design is generally allowed under the Concrete Code, the yield line method adopted by Mr. Southward, as provided in the US code (i.e. AASHTO LRFD Bridge Design Specification), is inappropriate in the present circumstances. Pursuant to CA 13.3.1 of the AASHTO (pp. 13-19 of the 2012 version)[1] (as extracted below), for such yield line analysis to be valid, stirrups or ties across the thickness of the wall have to be provided to resist the shear and diagonal tension forces. No such stirrups or ties have been provided in the trough walls in question.

> *"CA13.3.1*
> *The yield line analysis shown in Figures C1 and C2 includes only the ultimate flexural capacity of the concrete component. Stirrups and ties should be provided to resist the shear and/or diagonal tension forces. ..."*

[1] I do not possess the 2017 version as referred to by Mr. Southward in his COI-2 report.

Section 5: - Shear Links

35. In the Verification Report, in view of the concern about the unsatisfactory shear link placement in Area A of the NSL slab adjoining SAT and after design checks, MTRCL proposed suitable measures to be implemented at SAT.

36. **Section 5.3 – EIC shear calculation of SAT slab area**. Mr. Southward referred to EIC's shear calculations that take into account of: - (a) the correct tensile steel area, (b) the so-called higher in-situ concrete strength obtained from tests performed on concrete cubes prepared on site and (c) redistribution of shear forces.

37. My comment is that, regarding (a), "the correct tensile steel area" may have certain contribution effect which in fact has now been corrected in MTRCL's latest amendment submission. Yet suitable measures are still required in some locations. Regarding (b) high concrete strength and (c) redistribution of shear forces, I have reservations on Mr. Southward's comments.

38. Regarding the adoption of a higher concrete strength in Mr. Southward's calculation, I have the following comments/objections:

    (1) One can only adopt a higher concrete strength in structural assessment provided that Leighton had elected to use a higher grade of concrete (with higher design concrete strength) at the time of construction to replace the specified concrete grade in the accepted design. For the purpose of structural design or subsequent structural assessment, the concrete strength to be adopted depends on and is governed by the strength of the design mix of concrete adopted at design stage. If the design mix proposed by Leighton for the project at the time of construction was Grade 40D/20, and the said design mix was approved/accepted by MTRCL accordingly, Mr. Southward should use the concrete strength of Grade 40 in his design checks. The higher concrete strengths as may be obtained from the laboratory tests performed on concrete cubes prepared during construction stage should not be taken as the actual concrete strength in the structure. The compressive strengths obtained from concrete cube tests are always higher than the actual strength of the concrete in the structure even if the cubes were prepared from the same batch of wet concrete delivered to site. It is because the concrete

cubes were separately compacted and cured in the curing tank on site under ideal condition before they were tested. Hence, they do not represent the actual concrete strength in the structure. As such, the cube test results can only be used for the purpose of quality control rather than as a justification for a higher concrete strength in the structure.

(2) For the purpose of structural design or as in the present case structural assessment of an as-built structure, if one is to make an assessment on the basis of the actual strength of the concrete in the structure, one should first establish the characteristic strength of the concrete in the structure. To do so, one should take actual core samples from the structure and determine the actual strengths of the concrete cores by laboratory tests.

(3) It is well known and commonly accepted that cores extracted from the structure is a much better representation of the actual concrete strength in the structure.

(4) Since no concrete cores have been taken by Leighton or Mr. Southward from the structure for the determination of the actual strength of the concrete, the actual strength of concrete in the structure remains unknown.

(5) Lastly, even if concrete cores are to be taken for the said purpose, in order to establish the characteristic strength of the in-situ concrete for the purpose of structural assessment, one has to ensure that sufficient number of core samples are extracted from the structure so as to enable the characteristic strength to be established on proper statistical basis.

39. Regarding Mr. Southward's argument about redistribution of shear forces, I refer to Figure 8 of his COI-2 report. In Figure 8, he suggests that the shear force at NSL slab can be redistributed through an internal wall upward to the OTE slab above. This does not make engineering sense:-

(1) Since the internal wall in Figure 8 of his COI-2 report for SAT has been modeled by Atkins as part of the original structure in its structural analysis, internal forces predicted by simulation are deemed to exist after considering the stiffness, loading, boundary conditions and initial conditions of the structure with the internal wall in place (see **[AA2/553]** and **[AA2/748]**).

(2) Accordingly, there can be no further redistribution of loading unless the structure is being further modified.

(3) Further, redistribution of internal forces would require sufficient ductility for displacement to take place before any internal forces could be transferred to or taken up by other sections.

(4) Shear failure is a brittle failure which involved no play of ductility.

(5) Accordingly, there should be no redistribution of shear forces before failure of overstressed section.

40. As I have explained in my COI-1 Report (the relevant extracts of which have been reproduced in **Appendix JL2-A**), to be able to conclude that a structure is "safe" and "fit for purpose", the design must meet the requirements in the Concrete Code and NWDSM **[OU6/3753-3920]**. The large amount of calculations done by MTRCL on the basis of the design parameters under the Updated Design, and the recommendation for various suitable measures are intended to bring the as constructed structure back to a state that meets such requirements.

41. In summary, Mr. Southward's COI-2 report sought to criticise MTRCL's investigation and Updated Design. Meanwhile, however, it appears that Mr. Southward has not provided sufficient test results or analyses to dispute MTRCL's investigation and Updated Design. In my opinion, the structural assessment under the Updated Design done by MTRCL and its DDC and the subsequent detailed design for suitable measures made in compliance with the Concrete Code and MTRCL's NWDSM are in order.

Declaration

I, Dr. James Lau, declare that:

1. I understand that my duty in providing written reports and giving evidence is to help the COI, and that this duty overrides any obligation to the party by whom I am engaged or the person who has paid or is liable to pay me. I confirm that I have complied and will continue to comply with my duty.

2. I confirm that I have not entered into any arrangement where the amount or payment of my fees is in any way dependent on the outcome of the case.

3. I know of no conflict of interest of any kind in taking up this case.

4. I do not consider that any interest which I have disclosed affects my suitability as an expert witness on any issues on which I have given evidence.

5. I will advise the party by whom I am instructed if, between the date of my report and the trial, there is any change in circumstances which affect my answers to points 3 and 4 above.

6. I have shown the sources of all information I have used.

7. I have exercised reasonable care and skill in order to be accurate and complete in preparing this report.

8. I have endeavored to include in my report those matters, of which I have knowledge or of which I have been made aware, that might adversely affect the validity of my opinion. I have clearly stated any qualifications to my opinion.

9. I have not, without forming an independent view, included or excluded anything which has been suggested to me by others, including my instructing lawyers.

10. I will notify those instructing me immediately and confirm in writing if, for any reason, my existing report requires any correction or qualification.

11. I have acted in accordance with the Code of Conduct for Expert Witnesses as contained in Appendix D to the Rules of the High Court (Cap 4A).

Statement of Truth

I confirm that, insofar as the facts stated in my report are within my own knowledge, have made clear which they are and I believe them to be true, and that the opinions I have expressed represent my true and complete professional opinion.

Signature ____________________

Dr. James Lau, PhD, BBS, JP.
Authorized Person
Registered Structural Engineer
Registered Geotechnical Engineer