Legislative Council Panel on Transport
Subcommittee on matters relating to railways

Government's Assessment on the Investigation Report by KCRC on East Rail Underframe Equipment Mounting Cracks

PURPOSE

This paper sets out Government's assessment on the investigation report by the Kowloon-Canton Railway Corporation ("KCRC") on the root causes of the East Rail underframe equipment mounting cracks and the proposed permanent rectification measures.

BACKGROUND

2. In relation to KCRC's East Rail underframe equipment mounting problem, Members were briefed on the immediate actions taken by Government to monitor the effectiveness of KCRC's interim mitigation measures and inspection activities. The details were set out vide Government's papers presented to this Subcommittee at the meetings held on 18 January 2006 and 17 February 2006. Subsequently, KCRC completed its investigation and submitted its report to Government on 3 May 2006 for evaluation. KCRC also briefed Members on its findings at the Subcommittee's meeting held on 6 May 2006.

Summary of KCRC's identified root causes

3. Briefly, the root causes identified by KCRC are as follows-

(a) the dominant cause of the cracks found in underframe equipment mounting brackets, with the exception of those involving the air compressors and motor-alternators, is established to be excessive vibration induced by resonance oscillation of the car-body due to undulations on some sections of the rails. Weld imperfections and stress concentration areas found through metallurgical examinations

also contributed to the cracking of the brackets; and

(b) for the cracks in the mounting brackets of air compressors and motor-alternators, the dominant cause of the cracks is established to be weld imperfections. Apart from the excessive vibration through the train body (as explained in (a) above), the mounting brackets of air compressors and motor-alternators are also subject to further vibration induced by their moving parts.

Government's approach to assess KCRC's report

4. The Hong Kong Railway Inspectorate ("HKRI"), Electrical and Mechanical Services Department ("EMSD") and Highways Department ("HyD") formed an expert team in January 2006 to monitor the investigation undertaken by KCRC. To ensure robustness of Government's assessment, an international railway expert, Lloyd's Register Rail, was engaged to provide advice to Government in this evaluation.

5. The objectives of Government's assessment are to verify whether KCRC's suggested root causes are valid and whether the proposed rectification measures are effective to prevent recurrence of similar problems.

6. To arrive at an independent and thorough assessment on KCRC's investigation, our expert team and overseas consultant have undertaken the following activities-

(a) reviewed the technical reports and test data prepared by KCRC and its consultants;
(b) observed data collection on vibration;
(c) examined the modeling of various tests;
(d) witnessed test runs;
(e) conducted interviews with KCRC and its consultants as well as train manufacturers;
(f) reviewed literature on relevant standards and research reports; and

(g) consulted relevant experts in the field.

GOVERNMENT'S ASSESSMENT

KCRC's approach to identify the root causes

7. We note that KCRC has put in painstaking efforts in exploring possible causes of the incident during the investigation and undertaken numerous detailed analyses from various directions in a relatively short period. The Corporation has appointed the original train manufacturer, engineering consultants and university professors to provide assistance in the process. It has also appointed an independent review panel to scrutinise the findings.

8. We consider that KCRC has investigated the major issues that could have contributed to the development of the cracks. KCRC's investigation has examined possible causes including those which are vibration related, manufacturing related, maintenance related, projects related, operational and environmental related.

9. On the above basis, we consider that the scope of KCRC's investigation is comprehensive and that the Corporation has taken a scientific approach in identifying the root causes.

Validation of root causes identified by KCRC

10. Although the evidence for the causal factors as presented by KCRC may not be entirely exhaustive, we consider that KCRC has identified the major causes leading to the problem with cracks.

11. The Government's detailed assessment, incorporating Lloyd's Register Rail's inputs, is set out in the ensuing paragraphs.

(i) Excessive vertical vibration caused by resonance

12. Through reviewing the measurements and tests undertaken by KCRC, we accept that the excessive vertical vibration experienced by the

trains is one of the dominant causes resulting in the underframe equipment mounting cracks.

13. The measurements show that the vertical vibration experienced by the trains has exceeded the design criteria of the mounting brackets by a factor of two with peaks almost three times the design criteria. In the lateral and longitudinal directions, the measured vibrations generally fall within the design criteria.

14. KCRC considers that the excessive vertical vibration is caused by resonance induced by a combination of three factors interacting with each other. They are, first, the undulation pattern on the rail top with a longitudinal pitch of 3.1m and a vertical profile of less than 1 mm; secondly, the train speed of 70-90 kph; and thirdly, the natural frequency of 7 – 9 Hz of the car-body. When trains run at speeds of 70 – 90kph over this type of rail with undulations, the motion of the trains excites the car body at its natural frequency resulting in car body resonance.

15. Based on the data and test results, we accept KCRC's explanation that the combination of the above three factors has led to resonance, resulting in excessive vertical vibration experienced by these trains and consequently the material fatigue causing cracks to appear in the underframe equipment.

16. For the rails, we note that there is a strong correlation between the excessive vibration and a particular type of rail identified as PZ98/99. This evidence suggests that PZ98/99 rail may have directly contributed to the problem of excessive vibration by resonance.

(ii) Poor welding of underframe equipment mounting brackets

17. We note that the metallurgical examination on the underframe equipment and Magnetic Particle Inspection (MPI) check has confirmed that there is inferior quality of welding at the brackets, e.g. poor welding fusion. We also note in the crack analysis that cracks were initiated at locations of welding imperfection. It is thus evident that poor welding quality could be another dominant cause of the fleet-wide problem.

(iii) Underframe equipment mounting bracket material and design

18. As regards the materials used for the brackets, our review of the documents from KCRC reveals that the original material specifications for brackets given on design drawings appear to be consistent with materials used in the rail industry at the time of manufacture. Hence, we consider that the materials of the brackets should not be a contributory factor to the cracks.

19. While we note the finite element analysis[1] demonstrates that the loading requirements of the equipment mountings have met the UK rail industry standard, we find that the bracket design has in fact failed in the following aspects-

(a) the finite element analysis has shown that some of the equipment mountings do not meet the standard for stiffness. This has increased the effect of the resonant couple. As the impact of the vibration on these mountings is amplified, they have incurred more fatigue damage. We consider this a key factor which is not mentioned in the KCRC report. We note that KCRC, however, has plan to address these problems through the redesign of the brackets; and

(b) in the case of the compressors, we note that those with cracks are mostly in the batch of trains supplied in 1990, and that the compressor brackets were machined off on one side (out of 4 sides) from the designed thickness of 31mm to the worst case of 19mm, effectively removing the weld on one side. Finite element analysis by KCRC indicates that these mountings would have survived the excessive vertical vibration had the weld not been removed by machining. We consider that this suggests poor processes for control of the implementation of the bracket design.

[1] Finite Element Analysis is a computerised tool for analysing the strength of structure. It is widely used in mechanical and civil engineering. In this paper, the finite element analysis is carried out by KCRC and its consultant.

(iv) Suspension

20. The testing of the suspension and damping systems during the course of investigation reveals that the suspension and damping systems do not adequately attenuate the vibration levels currently experienced so that the vibration passes through to the car body allowing resonance to occur. KCRC has not considered this point as a contributing factor for the cracks but has recommended enhancing the suspension as part of the rectification measures. We have reviewed that at the time of design of such systems, the manufacturer did take into consideration the train and track parameters to satisfy the design criteria. However, it is unlikely that vertical vibration caused by an undulation with 3.1 m wavelength as currently seen on East Rail was anticipated at that time.

Other factors which Government considers KCRC should pay attention and require further follow up actions

(i) Automatic Train Operation

21. The Automatic Train Operation ("ATO") is a service performance related system which enhances the effectiveness of the railway services. Its primary function is to automatically drive trains according to a preset speed profile.

22. We accept that ATO is not a direct cause of the cracking because the associated acceleration and braking rates are found to be within the original car specifications and have not introduced excessive stress to the underframe equipment mounting brackets.

23. KCRC has decided to drive trains manually in January 2006 so as to reduce the maximum speed from 120kph to 110kph and reducing the speed to 70kph when entering stations. The modified ATO which KCRC intends to re-introduce is to emulate as much as possible this manual mode driving of trains at reduced speed which has been in use for the last few months. The modified ATO could help reduce the amount of time spent on the critical speed band of 70-90 kph which induces

resonance vibration. HKRI is now examining and monitoring the testing of the reliability of the modified ATO system. After completion of the test runs, HKRI will approve KCRC's application for the re-introduction of ATO.

(ii) Crack detection during maintenance

24. We have examined KCRC's maintenance regime to find out why the maintenance activities have missed the cracks on the compressor which failed on 21 December 2005 and also those appeared fleet-wide. We have looked into four maintenance activities that may present an opportunity for KCRC to identify the cracks in the underframe equipment. These are explained in the following paragraphs.

(a) Regular inspections

25. KCRC staff carry out visual examinations of all underframe equipment on the cars as part of their regular inspections schedule. KCRC's procedures for this examination calls for "visual inspections" to be carried out on most items of underframe equipment. The staff who carry out these "on car" inspections are trained internally and are not specifically trained to look for cracks. Though lighting underneath the cars is in line with industry standards, we acknowledge that visibility is limited given that the equipment is painted, dirty and difficult to access. It is therefore reasonable that the hairline cracks would be particularly hard to detect during these regular inspections.

(b) Overhaul of Underframe

26. At the regular overhaul every 3 years, the underframe is cleaned and visually inspected for various possible problems including cracks in underframe equipment brackets. The paint is, however, not removed. KCRC's procedure requires visual examination for signs of damage, cracking and deformation. However, this clear instruction will be ineffective if the hairline cracks are small, because of the paint and lighting conditions. KCRC workshop staff also mentioned that the cleaning equipment used is not totally effective.

(c) Overhaul of Components

27. At the component overhaul every 3 years, major equipment is removed from the car, cleaned, and worked on in good lighting in the workshop allowing the best opportunity for cracks to be seen. From the documents presented by KCRC, there is no evidence to show that its procedures specifically point the staff to inspect for cracks. In spite of this, we consider that it is not unreasonable to expect that workshop staff should notice large cracks in brackets or welds, if they are present, as the items have been cleaned and the lighting is good. We assess that the largest cracks seen on the brackets of the two compressors may have already been developed into sizeable cracks at the time of last overhaul in early 2005. If this was the case, it is reasonable to expect that KCRC maintenance staff should have detected such cracks if they are visible on the surface during the overhaul of component. The explanation offered by KCRC for staff missing the cracks during overhauls is that they were concentrating on the interior parts of the compressors rather than the external mountings. Moreover, as the procedures now stated, staff are not conditioned to look for cracks and poor welding. These defects could go unnoticed if the maintainer is not vigilant.

(d) Recommissioning

28. At recommissioning when all the overhauled equipment is reinstalled onto the underframe the procedure calls for visual inspection of "all component mounting brackets for signs of cracking or damage". However, at this stage all equipment has been painted and so only very large cracks could possibly be noticed.

29. Thus for general inspection it is considered that the constraints in the conditions of inspection would prevent the detection of hairline cracks. For overhaul of components, the inspection conditions are reasonable to detect cracks in the weld provided that they are sufficiently large and visible at the surface. Having reviewed the photographic evidence and considered the assumptions of the crack propagation rate, we consider that it is reasonable to expect that cracks for the two compressors with the largest cracks should have been visible and detected at the time of the last overhaul in early 2005. Our recommendations to KCRC for improving

its maintenance activities are given in paragraph 46 below.

Factors which are unlikely to have contributed to the cracks

Environmental and operational factors

30. On the evidence presented by KCRC, we have no reason to consider environmental and operational factors (e.g. changes in passenger loads and weather) as causes.

Procurement and acceptance procedures of rails and trains

31. The dominant causes of the fleet-wide cracks are insufficient flatness (undulations) of the rail top on a particular batch of rails and inferior welding quality of the underframe equipment. We therefore consider that it is imperative to examine KCRC's procurement and acceptance procedures of rails and trains in order to identify whether there were weaknesses which warrant improvements. Our findings are set out below.

Rails

32. For the procurement of PZ98/99 rail in 1998/1999, a specification was produced by KCRC based on international practice at the time. KCRC also appointed an independent specialist agent to assure the quality of the rail produced by the supplier.

33. For rail top flatness, although there was no international standard in place then specifically on this aspect, we notice that at the time of procurement, KCRC did specify criteria for rail top flatness based upon an emerging standard at the time. This specified a vertical flatness tolerance of up to 0.4mm over 3m lengths of the rail, which is in fact in line with the subsequent new European standard adopted in 2004. KCRC's appointed agent also assessed the rail top flatness and certified that the PZ98/99 rail met the rail top flatness specification. The method of assessing rail flatness by the appointed agent at the time was to use a straight edge in accordance with the specifications. Nevertheless, we note that the technology of measuring rail top flatness at that time was

still developing since the specification on rail top flatness was new. This straight edge method, by today's standard, might not have been the most sophisticated method to check the rail top flatness, although serious undulations of up to 1mm could possibly have been found by this method.

34. In our assessment, we have also asked KCRC to send the spare parts of the rails in question for laboratory testing to ascertain whether the materials of the problematic batch of rails meet the specification in terms of hardness and the specified composition. The laboratory test result shows that the materials used for the rails have met the procurement specifications.

35. In light of the above findings, the source of the undulations has not been fully established. This may be from the PZ98/99 rail original manufacture or imprinting during operations or a combination of both. On this, long-term monitoring and further analysis by KCRC will be necessary.

Trains

36. As regards the train procurement procedures adopted by KCRC, we note that the general practice adopted by KCRC all along has been to engage specialist inspection agent to carry out the examination of trains at the time of procurement. The underframe equipment at issue, together with thousands of components, was supplied to KCRC with the trains acquired. Acceptance tests were carried out in accordance with industry norm by KCRC's appointed agent where these tests focused on the overall performance of the trains and sub-systems. KCRC monitored the agent's work through regular review meetings and discussions where necessary.

37. With specific regard to the defects in welding for the compressor and mounting brackets in question, we have enquired and KCRC explained that the Corporation does not possess the associated design drawings since such drawings would only be made available by the underframe equipment manufacturer to the car-builder. This is in line with the prevailing industry practice that the contract of procurement of

trains is performance-based and that the design of the underframe equipment is a matter for discussion between the car-builder and its equipment manufacturer.

38. In response to our enquiry, KCRC confirmed at the time of procurement, neither the Corporation nor its appointed agent was informed by the car-builder or equipment manufacturer of the compressor mounting bracket dimension being reduced from the designed thickness of 31mm. The Corporation indicates that in accordance with industry practice, it would not focus on the details relating to such items as mounting brackets of equipment unless it has reason to suspect the integrity of such items. Inspections would be undertaken by the appointed agent essentially by visual inspection and non-destructive tests. For defects such as the weld quality, they can only be identified by destructive test which would only take place if there is, as a consequence of the visual test, reason to suspect the possibility of cracking or other defects. On the basis of the information available to KCRC at the time of procurement, it considered that no defects were suspected during testing conducted in respect to the train sets supplied to the Corporation.

39. Based on the above, we note that KCRC has adopted a performance specification for the train procurement and appointed a competent inspection agent to assure the quality of the trains. This was consistent with the railway industry's good practice. Nevertheless, we consider that KCRC should tackle with the car-builder the problems of machining off on one side of the brackets of the compressors and the weld imperfections. KCRC should also improve the technical areas in the procurement and acceptance procedures such as those set out in paragraph 48 below.

KCRC's proposed rectification measures

40. In its investigation report, KCRC has proposed the following key mitigation measures-

a) strengthening of equipment mountings;
b) enhancement of the suspension system;

c) revision of maintenance schedule;
d) installation of train-based and track-based instruments for surveillance of the wheel-rail interaction; and
e) replacement of the PZ 98/99 rail.

41. Government agrees in principle with the above measures proposed by KCRC. To ensure their effectiveness, HKRI will ask KCRC to submit further details of the proposed measures for HKRI's evaluation before actual implementation. In particular, we consider that any modification to the suspension system should be carefully assessed given that it might impact on other parts of the train system, e.g. on the interface of the suspension system with the train body etc. The proposal requires a thorough examination of its feasibility before implementation.

Government's proposed rectification measures

42. Apart from the two measures mentioned in items (a) and (b) above to enable the trains to tolerate the existing levels of vibration, we consider that KCRC should undertake the following measures to directly address the source of vibration.

(a) Prevent or minimise vibration and car-body resonance

(i) Replacement and grinding of rails

43. While we support the proposed rail replacement in principle, we recommend that KCRC should consider replacing the worst sections on a priority basis. KCRC should also explore whether rail grinding technology is readily available for it to detect minute undulation during routine track survey and to help smooth the undulations with a view to reducing the vibration.

(ii) increase stiffness of car-body

44. The existing natural frequency of the East Rail car-body with cracks is around 7 Hz - 9Hz and that it would be induced to resonance when the train is travelling at a speed of 70-90kph at sections of rails with undulations. We consider that KCRC should explore feasibility and

cost-effectiveness of increasing the stiffness of the car body during its regular overhauls so as to eliminate or minimise exposure to the resonance vibration problem. The Corporation should also fully take into account the relationship between the natural frequency of the car body and possible resonance in future train refurbishment programme or procurement of new trains.

(b) On-going monitoring

45. On-going monitoring and surveillance are important to identify any potential causes not yet revealed and ensure the effectiveness of the remedial measures. We notice that KCRC would install train-based and track-based instruments for surveillance of the wheel-rail interaction in order to measure levels of stress occurring in the equipment mountings and other sensitive locations of the vehicle. Apart from this measure, we recommend that KCRC should also-

(i) monitor the running rails at various locations throughout the tracks, and in particular in locations of adverse surface undulation. This will help ascertain whether the undulation amplitude and wavelength is in a steady state condition, and whether the rest of the track will remain in a healthy condition over time;

(ii) maintain vigilance on other aspects of the rolling stock that may be susceptible to vertical vibration modes i.e. car body and bogie structure, relay/contactor reliability and interior fitting attachments; and

(iii) monitor wheel roundness and wheel balancing processes to minimise the possibility of excessive vibration.

(c) Enhancement of maintenance

46. KCRC's day-to-day maintenance practices are consistent with those practised by railways internationally. The frequency of maintenance carried out by KCRC is either equal to or even higher than other railways. However, meeting international practice does not

preclude the opportunity for weaknesses to be present in the system. In light of this underframe equipment mounting problem, we consider that the following improvements should be made to the maintenance regime-

(i) the procedures for inspections and overhauls need to be revised to focus on cracks detection in a way that is more effective;
(ii) training on recognising poor welding and where cracks may occur should be given to all workshop staff;
(iii) underframe cleaning method needs to be reviewed in order to enhance visibility for more effective detection of cracks;
(iv) there should be more frequent replacement of the resilient mounts. The resilient mount's function is to help absorb part of the vibration at the brackets. KCRC's current replacement period of the resilient mounts is 12 years, which is too long. Resilient mounts are generally considered a consumable in the rail industry and should be replaced every 3 years;
(v) KCRC should specify a maximum level of vibration as part of the acceptance criteria for rotating equipment after overhaul; and
(vi) KCRC should carry out vigilant maintenance on other types of trains to ensure that the causes contributing to the East Rail problems would not repeat in other trains and railway lines.

(d) Enhancement of procurement and acceptance of trains and rails

47. KCRC should evaluate the lessons learnt. We are of the view that KCRC should consider including stricter requirements on manufacturers' process control and quality control as well as the process of acceptance in future procurement of new trains and rails.

48. For procurement of trains, we consider that KCRC should introduce the following improvements-

(a) to instruct the appointed inspection agent to pay attention to, apart from other items, the underframe equipment brackets, e.g. sample checking of items in factory and during acceptance of trains by more vigilant methods; and

(b) to require the car-builder to fully disclose any variation to the specifications which could affect the performance of the equipment.

49. For procurement of rails, KCRC should continue to rigorously assess and keep watch on the suppliers' quality to ensure that they are capable of fully satisfying the procurement specifications. As regards the inspection of rails by the appointed agent during the acceptance process, the Corporation should set out comprehensive instructions for the agent to ensure that the inspection process is robust, and the inspection work is conducted by using the latest technology.

(e) *Asset management*

50. We notice that while KCRC has maintenance plans for each asset group, the Corporation has not produced a fully integrated asset management system. Asset management system of a railway corporation refers to the management of essential assets including rolling stocks, tracks, signalling systems and train equipment etc. Having an integrated asset management system is important because it will enable the Corporation to monitor the impacts of measures taken in one asset on the others, and to help evaluate whether the measures taken as a whole are efficient and cost-effective and whether the whole system is capable of coping with changes in operating environment throughout its design life.

51. We consider that there is a lack of a system approach to asset management for KCRC and there is a tendency for individual departments to operate within their individual disciplines. KCRC so far could maintain the integrity of its asset management because of the high competence of the maintenance engineers and staff. Moreover, there is evidence that maintenance reflects the status quo in some areas, rather

than developing continuous improvement.

52. We consider that KCRC Management should expedite the development of a formal and integrated asset management system in line with the emerging best practices and to take into account the future demands on its services. This will not only help ensure that the assets are able to sustain their performance throughout their life cycle, but also enable KCRC to more effectively detect and prevent recurrence of major fleet-wide problem at the scale of this East Rail incident which required immediate, sudden and massive efforts from all parties to arrest the problem.

53. Moreover, crack management is not a new concept in the rail industry. From time to time, various railway corporations might have discovered cracks and taken early actions to rectify them so as to prevent the cracks from developing into a serious fleet-wide problem. We consider that KCRC Management should be more vigilant and alert in developing a regular programme to detect and manage cracks.

(f) *Safety management*

54. While the safety management manual of KCRC meets the requirements of international best practice, the Corporation's safety management system has allowed different departments to develop and implement their own processes to achieve the requirements. The response to the underframe cracking incident appears to have highlighted other interface weaknesses in the system. On one hand, the incident appears to be treated as a technical failure and as such is managed by the Rolling Stock Department who informed the Safety and Quality Department of their findings and action. The incident has also been declared a corporate crisis. Neither the Divisional nor Corporate systems initially triggered a requirement to undertake a system wide risk assessment to examine the incident and the impact of short, medium, and long term changes on the safety and business risks.

55. We recommend that KCRC should conduct a review of the linkage of the safety management system from Corporate to Departmental levels. Improvements are required in the examination and

incorporation of best practice (both internal and external) throughout the safety management system.

56. A list of Government's recommendations to KCRC for improvement is summarised at the Annex.

Way Forward

57. HKRI would monitor the implementation of the above required improvement measures by KCRC and request the Corporation to regularly report the work progress and result of the long term monitoring process.

Environment, Transport and Works Bureau
July 2006

Annex

List of Government's recommendations to KCRC for improvement

Recommendation 1: should work out the detailed design for strengthening the equipment mountings and enhancement of the suspension system.

Recommendation 2: should consider replacing the worst sections of the rails with undulations on a priority basis.

Recommendation 3: should explore whether rail grinding technology is readily available to detect and remove the undulations.

Recommendation 4: should explore feasibility and cost-effectiveness of increasing the stiffness of the car body during the regular overhauls.

Recommendation 5: should work out the implementation details of the train-based and track-based instruments for surveillance of the wheel-rail interaction.

Recommendation 6: should monitor the running rails at various locations throughout the tracks.

Recommendation 7: should maintain vigilance on other aspects of the rolling stocks that may be susceptible to vertical vibration mode.

Recommendation 8: should monitor wheel roundness and wheel balancing process.

Recommendation 9: should revise the procedures and training for inspections and overhauls to incorporate crack detection and management.

Recommendation 10: should conduct training on recognition of poor weld quality for all workshop staff.

Recommendation 11: should review underframe cleaning methods.

Recommendation 12: should increase the frequency for the replacement of resilient mounts to occur at each overhaul.

Recommendation 13: should specify a maximum level of vibration as part of the acceptance criteria for rotating equipment after overhaul.

Recommendation 14: should carry out vigilant maintenance in other trains and railway lines of KCRC.

Recommendation 15: should consider including stricter requirements on manufacturers' process control and quality control for new trains and rails.

Recommendation 16: should consider including stricter requirements on the process of acceptance in future procurement of new trains and rails, e.g. by instructing the appointed inspection to conduct sample checking of items in factory and during acceptance stage, and setting comprehensive instructions for the appointed agent to conduct the inspection using the latest technology.

Recommendation 17: should expedite the development of a formal and integrated asset management system.

Recommendation 18: should conduct a review of the linkage of the safety management system from Corporate to Departmental levels.

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