RIGA TECHNICAL UNIVERSITY

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ASSESSMENT OF REMAINING RESOURCE OF TANK WAGONS WITH EXPIRED LIFE TIME

Summary of Doctoral thesis

Riga 2013

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DOCTORAL THESIS
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Doctoral thesis for receiving Doctoral degree in engineering sciences is publically defended on December 09, 2013, at 14^{30} in Riga Technical University, Faculty of Transport and Mechanical Engineering, Lomonosova street 1A, building k-1, in 218 Auditorium.

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CONFIRMATION

I confirm that I have elaborated this Doctoral thesis, what is submitted for examination in Riga Technical University for receiving Doctoral degree in Engineering sciences (or other). Doctoral thesis is not submitted in any other university for receiving scientific degree.

Aleksandrs Boiko …………………………….(Signature)

Dates: ………………………

Doctoral thesis is written in Latvian, contains introduction, 7 sections, Conclusion, Bibliography, 10 appendices, 147 figures and illustrations, in total 175 pages. Bibliography contains 76 titles.

Terms

Terms are consistent with Academic term data base of Latvian Academy of Sciences AkadTerm [http://termini.lza.lv/index.php?category=9] and Glossary of terms of SJSC Latvian Railway.

1) remaining resource – summary operation time of object (rolling stock, its nodes and aggregates) from control moment of its technical condition up to transition to border state; Load-bearing element with minimal remaining resource determines tank wagon resource in general.
2) determined life time – calendar duration of operation, by reaching witch the operation should be terminated regardless its technical condition;
3) life time - calendar duration of operation from starting operation of object or from its renovation to transition in limit state position;
4) operation – stage of product's life cycle, where its quality is exercised, maintained, and restored, with which one usage of product according to its aim is performed;
5) cyclic load – it is characterised by changes of (casual) load amplitude, which reoccurs in definite time interval (see Fig. T1).
6) sweep (for stress) – summary value of amplitude from minimal to maximal meaning (without taking into account the marks) (see Fig. T1).

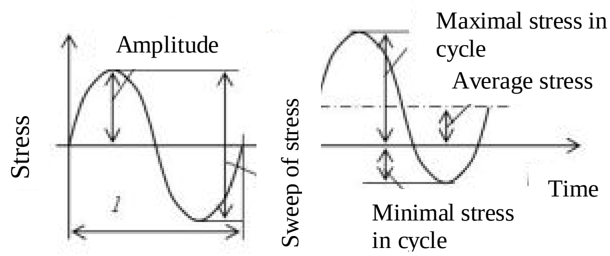

Figure T1

7) life time extension – determination of new life time for rolling stock;
8) limit state – state of rolling stock, in case of which the further operation is not allowable or is not rational, or renewal of operational state of it is not possible or rational;
9) wagon owner – natural or legal person who has ownership of railway rolling stock;
10) railway rolling stock – towing vehicles (locomotives), wagons, self-propelled vehicles, intended for transportation of passengers, baggage, cargoes, freight baggage and postal dispatches along railway;
11) regular decoupling repair of wagon; TR: repair, performed to ensure or restore capacity of wagon, by replacing or restoring individual parts on specialised roads. According to state of freight wagon, place of damage detection and decoupling, regular decoupling repair is divided into:

    - regular wagon repair; TR-1: wagon repair without cargo, which is performed by preparing it for transportation, decoupling from rolling stock of wagon group, by moving it to special roads with transportation to non-operational fleet. In addition, transportation to non-operational wagon fleet, which belongs to administration of infrastructure or owner, procedure for personal wagons, which are recorded to administration, is determined by administration of this railway or owner;

    - regular wagon repair; TR -2: repair of freight wagon with cargo or without it with decoupling from transit trains and trains, which have arrived to distribution, of from executed stocks, their transportation to non-operational fleet with feed on specialised roads.

12) depot repair of wagon (further DR) – repair, which is performed to prevent damages or partially restore wagon resources with replacement or restoration of limited nomenclature components, and control of technical condition of components;
13) capital repairs with extension of useful life time (further KRP) – technical condition control of load-bearing elements of whole wagon with complete or almost complete restoration of wagon resources, replacement and restoration of any component of it, including base elements and determination of new life time.
14) load-bearing element of tank wagon – load-bearing elements of tank wagon are boiler, wagon frame, trolley frame, overspring beam of trolley frame. In this research trolley frame and overspring beam of trolley frame are not discussed. Load-bearing element with minimal remaining resource determines tank wagon resource in general.

Topicality of Doctoral Thesis

In tank wagon fleet of Latvian Railway tank wagons, carrying liquid and flammable cargoes, are the most dangerous from the security aspect. In the Paper are discussed for-axle tank wagons, for which ones in cyclic load the life time has expired. Tank wagons are intended according to accepted Standards [1] by determined load regimes and they possess required reserve strength within life time period, determined by manufacturer – during 32 years. According to normative documents life time of tank wagons may be extended up to one and a half of term, so it is determined extension of life time up to 48 years. However, in conditions of aging fleet and existing system of planned repair works of depot and performance of general capital repairs, damages of fatigue load-bearing elements (in this Paper only damages of boiler and frame are discussed) occur already in first months of warranty intermediate repair period (2-3 years) [2], and by increase of life time their amount only increases. Damages are prevented according to Manual of repairs for freight wagon [3]. According to data of Russian Railway [4] during 5 years from 2001 to 2005 a part, when tank wagons were decoupled from stock and sent for current repairs, forms 17.3 % from total amount to be decoupled due to found damages. According to data of SJSC Latvian Railway, number of decoupled tank wagons comprises around 0.5% of total amount of accepted wagons, which are seen in operation and recorded to various countries. However, number of decoupled tank wagons with life time, sent for regular repairs, increases with each year. In 2012 in comparison with 2011 their amount increased by 4 %, 57 % of which ones were decoupled from railway stocks in territory of Latvian Railway, which in total comprised more than 500 tank wagons. Thereby it is needed to clarify causes for occurrence of fatigue damages of load-bearing elements for tank wagons with already expired life time, and to discover possibility for existence of additional loading regimes, what decreases strength of tank wagon load-bearing elements (for boiler and frame) and remained resource, as well as to analyse quality of repairs and impact of welded joints to tank wagon resource.

Existing control and information collecting systems of rolling stock operation damages do not ensure collection of information on fatigue damages of tank wagon boiler and frame. Thereby it is necessary to perform examination of fatigue damage flow for tank wagons, existing into operation, and to elaborate new approaches and methods for diagnostic of tank wagons in operating conditions of SJSC Latvian Railway and to implement appropriate supplements in methodology of tank wagon diagnostics with purpose to extend their operation time, determined by manufacturing factory.

Now, according to Regulations on extension of operation time for freight wagons, which are running in international traffic, [5] and to Common methodological instructions on technical diagnostics of wagons [6] for assessment of remaining life time (resource) of tank wagons are required substantial costs due to required performance of impact tests of resources, during performance of which the wagon is lead to destruction after which it is excluded from operation. Thereby it is useful to assess remaining resource of tank wagons in way of calculations analytically, by using for remaining strength of load-bearing elements (boiler and frame) calculation software of ultimate elements (Nastran, SolidWorksSimulation, ANSYS, etc.). Thereby elaboration of methodology for determination of remaining resource for cyclic loadable tank wagons is topical. In methodology for each fatigue damage zone the appropriate calculation method of resource should be selected, which takes into account the different character of load, which cause damages in this zone.

Elaborated methodology for determination of remaining resource of railway cyclic loading tank wagons can be distributed also to other types of rolling stock. For its elaboration it is required to perform statistical processing of operation damages, to calculate strength of construction in general and in details in damaged areas. Theoretical researches in selection field of remaining resource assessment method are referable to each damaged area of tank wagons.

Aim and tasks of Doctoral Thesis

Aim of Doctoral thesis is to create methodologies for analytic determination of remaining resource for cyclical loading of tank wagons with expired term to increase operating safety of tank wagons in warranty intermediate repairs period.

To achieve above mentioned aim, it is required to solve the following tasks:

1. To collect data on operational damages for tank wagons with expired life time, to perform analysis of damages, to determine regularities of their distribution in warranty intermediate repair periods, to assess impact of regular repair on damage flow.
2. To elaborate calculation model of ultimate elements of tank wagon frame and boiler, to perform normative calculations of strength with purpose to determine main areas of increased load.
3. To discover causes for occurrence of load-bearing element damages for tank wagons with expired life time, by performing variational calculations of strength.
4. To justify calculation method of remaining resource for each zone of tank wagon damages, to perform calculation of resource of these zones, to assess impact of quality to resource.
5. To elaborate additional methodology for tank wagon diagnostics and location maps of possible damages, including fatigue damages.
6. To elaborate methodology for assessment of remaining resource for cyclic loadable tank wagons with expired life time.

Research methods

The main tasks of research were solved, by using statistical processing of collected data on operational damages of tank wagons. In strength calculations of tank wagon load-bearing elements there was used modern software of ultimate elements SolidWorks Simulation. Examination of common strength and discovery of increased tension zones of tank wagons in deviation from normative load regimes, which are determined in Strength calculation standards [1], was determined according to created calculation model for tank wagon frame and boiler.

Calculation experiments were performed for damage zones for assessment of impact of cracks and breaks to load-bearing constructions. Strength calculations [7] were performed for tank wagons before and after repairs (with strengthening shields, manufactured according to requirements of valid documents: Repair instructions [3] and Welding and melting instructions [8]). As well as there were performed strength calculations for various strengthening variants [9,10], which can be met into operation. Concentrator zones of damages and loads are more detailed in calculation model.

Elaborated recommendations for reading results of calculation models in damage zones with possibility to perform inspection of obtained results and comparison with test results.

For analytical calculations of remaining resource determination was used calculation software MathCad.

Results of performed statistical processing of data on tank wagon damages and experiment results of calculations, performed according to established model were compared with test results of wagons and results of other authors [11].

Scientific novelty and main results

Scientific novelty of Doctoral thesis:

1. There are determined distribution regularities of fatigue damages for tank wagons with expired life time in conditions of SJSC Latvian Railway.
2. Determination method for remaining resource of tank wagons for each zone of fatigue damages depending on load, which causes damages, and their reoccurrence is justified: from single impact loads to low-cycle and high-cycle load regimes. Its accuracy was assessed according to operational data on terms of damage occurrence.
3. Diagnostic methodology for tank wagons was supplemented, taking into account damages, which are not listened in existing normative documentation, which ones were discovered in operational conditions in SJSC Latvian Railway. Implemented supplements allow assessing of remaining strength for load-bearing elements in faster and more accurate manner with purpose to extend determined life time.
4. Elaborated methodology for remaining resource determination for cyclic loadable tank wagons, taking into account discovered additional load regimes (lateral swinging, relaying on non-active sleeper supports), what allows determination of remaining resource of tank wagon in any operational stage.

Main results of Doctoral thesis, proposed for defence:

1. Determined fatigue damage zones of tank wagons and assessed efficiency of existing planned repair system according to results of statistical processing of tank wagon damages.
2. Discovered main causes of damages for tank wagon load-bearing elements (loading regimes) in warranty intermediate repair period.
3. Strength and remaining resource of fatigue damage zones in tank wagon boiler and frame was assessed in way of calculations.
4. Discovered quality impact of repair work quality to remaining resource of cyclic loadable tank wagon boiler and frame.
5. Provided recommendations on organization and surveillance of welding works during performance of types of repair renewal.
6. Performed shape optimisation of boiler and frame support elements and strengthening shields in console part of tank wagon frame for decrease of load state by minimising their mass.
7. Prepared maps of tank wagon operational damages with fatigue damage zones, which are sorted in ascending order of occurrence frequency during warranty intermediate repair period.

Peculiarities of research are the following:

1. There are specified normative load calculation regimes, by assessing strength of tank wagon load-bearing elements. Discovered additional lateral swinging regime, which is main factor, which creates cracks in vertical wall of cross-beam in joints with basic beam.
2. Justified causes of operational damages in tank wagon boiler strengthening frame in main node (pads at frame plates). Variational calculations of strength have confirmed impact of

quality and length of perpendicular welded joints, by welding pads at boiler edge ring, to impact of cracks in given connection.

Practical application

Elaborated methodology for determination of remaining resource for cyclic loadable tank wagons and supplements of diagnostic methodology for tank wagons, calculation models for tank wagon frame and boiler allow:

1. to discover fatigue damages in earlier development stage (by performing visual and instrumentally technical inspection (defectoscopy) of tank wagons), which will decrease amount of fatigue damages during operation term, determined by manufacturing factory, and during warranty intermediate repair period;
2. to increase quality of repairs (taking into account supplements and recommendations on quality and performance of welded joints);
3. to decrease number of non-planned (decoupling) repairs and costs for cargo handling.

Elaborated methodology for determination of remaining resource may be used by producing and designing other types of rolling stock. Main direction of methodology is tank wagons with expired life time, determined by manufacturing factory.

Discovered regularities of fatigue damage flow distribution allow assessment of amount of damages during warranty intermediate repair period and correction of next planned repair work type (depot or capital repairs) to maintain safe technical condition of tanks in predictable operation term in conditions of SJSC Latvian Railway.

Justified method of remaining resource determination [12,13] puts forward the issue on performance of impact resource tests with destruction of tank wagons which is specially topical aspect for owners with small number of wagons.

Recommended activities in organization and surveillance of welding works [14-16] can be used in depot of wagon repairs, by performing renovation repair types.

Optimized shapes of boiler and frame support elements and strengthening shields [17-20], which were performed through use of calculation software EDAOpt [21-23] and SolidWorks Simulation, can be used in performing renovation repairs and designing new wagons.

Implementation

On the base of performed research on remaining resource of cyclic loadable tank wagons with expired life time [12], there are prepared and submitted proposals in administration of Latvian Railway for supplementation of Standards [1] for their submission in Dynamic and strength department of rolling stock in Russian Railway Research Institute, as well as there are prepared proposals for supplementation of Welding and melting instruction [3] for its submission to authorised wagon management specialists of Railway Administration in Railway transport Commission Council (now the proposals (see Appendix A1) are in examination of Ltd. “LDZ Ritošā sastāva serviss”). They are the following:

1. It is offered to supplement section 2 of valid Standards (Standards for calculation of forces and calculation of regimes) with additional lateral swinging regime, by assessing strength of freight wagon construction. Lateral swinging regime is proposed to be implemented as normative, respectively, observance of it should be mandatory.
2. It is offered to supplement paragraph 5.8.40 of section 5.8 (Cisterns) of valid Welding and melting instruction with sub-paragraph (c) in relation with length control of welded joint of pad at tank wagon boiler edge ring. Proposal is offered to be implemented as normative, respectively, observance of it should be mandatory.

3. It is offered to supplement valid Standards [1] with additional boiler edge ring reliance on upper sill supports (in case of wear of central supports) to assess strength of tank wagon constructions. Loading regime, when boiler edge ring is based on upper sill supports is offered to be implemented as additional regime.
4. It is offered to supplement reference 2653 (on performable repair works) and table of damage codes, traffic forms 1354 on exit from repairs, electronic data base of Engineering Computer Centre of Railway Administration with information on fatigue damages of tank wagon load-bearing elements (boiler and frame), which should be discovered during operation and before performance of planned repairs. It is offered to collect data on fatigue damages of tank wagons, which are running in international traffic.

Approbation of Doctoral thesis

It was reported on main achievements and results of Doctoral thesis, by receiving positive assessment in the following international scientifically technical conferences:

1. VIII International Conference on the Improvement of the Quality, Reliability and Long Usage of Technical Systems and Technological Processes Conference, 5-12 December 2009, Hurghada, Egypt.
2. International Symposium "Сварка и родственные технологии", 24 March 2010, Minsk, Belarus.
3. IX International Conference "ВИБРАЦИЯ-2010. Управляемые вибрационные технологии и машины", 12 – 14 May 2010, Kursk, Russia.
4. 7th International DAAAM Baltic Conference "INDUSTRIAL ENGINEERING", 22-24 April 2010,Tallinn, Estonia.
5. International Conference "Strength of Materials and Structure Elements" dedicated to the 100th birthday Georgy S. Pisarenko, 28 – 30 September 2010, Kyiv, Ukraine.
6. 7th International Symposium „Surface Engineering. New Powder Composition Materials. Welding", 23-25 March 2011, Minsk, Belarus.
7. 8th International DAAAM Baltic Conference "INDUSTRIAL ENGINEERING", 19-21 April 2012, Tallinn, Estonia.
8. 10th International Scientific Conference NOMATEX-2012, 12-14 September 2012, Minsk, Belarus.
9. 11th International Conference Vibroengineering 2012, 11-12 October 2012, Kaunas, Lithuania.
10. 2013 International Conference on MEMS and Mechanics (MEMSM 2013), 15-16 March 2013, Wuhan, China.

Publications

Main results, obtained in Doctoral thesis, and references are applied in the following scientific publications:

1. Januševskis A., Meļņikovs A., Boiko A. "Shape Optimization of Mounting Disk of Railway Vehicle Measurement System", Journal of Vibroengineering. - 12. (2010), pp.436.-442. (SCOPUS)

2. Boiko A., Auziņš J., Januševskis J. „Cisternvagona stiprības novērtējums pie daudzciklu slogojuma”, RTU Zinātniskie raksti.– Mašīnzinātne un transports. 6. sērija. Mehānika. 28.sējums (2008), 115.-120.lpp. (EBSCO)
3. Boiko A., Januševskis A., Meļņikovs A., Vučetičs I. „Vagona mērīšanas sistēmas konstruktīvās formas optimizācija. Constructive Shape Optimization of Wagon Measurement System”, RTU Zinātniskie raksti, 6.sērija, 33.sējums (2010), 78.-82.lpp. (EBSCO)
4. A.Boyko „Influence of barrel damages on life time of tank wagon, Katla bojājumu ietekme uz vagona cisternas kalpošanas termiņu”, Proceedings of 8th International DAAAM Baltic Conference "INDUSTRIAL ENGINEERING 19-21 April 2012, Tallinn, Estonia, pp.21.-26. (ISI WEB of SCIENCE)
5. Auziņš J., Boiko A., Januševskis A., Januševskis J., Kovaļska A., Meļņikovs A., Pfafrods J. „Mehānisko sistēmu modelēšanas, identifikācijas un daudzkriteriālās optimizācijas metožu un līdzekļu izstrāde mašīnu un mehānismu dinamikas laboratorijā. Development of methods and tools for simulation, identification and multiobjective optimization of mechanical systems at the machine and mechanism dynamics laboratory”, RTU 147. jubilejas zinātnisko rakstu krājums (2009), RTU, pp.19 - 26. ISSN 1407-8015
6. Boiko A., Balckars P., Auziņš J., Meļņikovs A. „Remonta stiprinājumu efektivitātes vērtējums cisternvagona fasonķepu zonā. Effectiveness evaluation of the repairs strengthening in the zone of shaped body support of the tank car”, RTU Zinātniskie raksti, 6.sērija, 32.sējums (2009), 12.-17.lpp. ISSN 1407-8015
7. A.Boiko, P.Balckars „Cisternvagona rāmja bojājumu un remonta kvalitātes analīze pamatsijas un pulkas sijas savienojumā”, RTU Zinātniskie raksti, 6 lpp. (In press). ISSN 1407-8015
8. Бойко И.Ю., Бойко А.Ф. „Повышение эффективности ремонтной сварки вагона-цистерны”, Международный симпозиум “Сварка и родственные технологии”, 24 марта 2010 года, Минск, Белоруссия, стр.81.-85.
9. А.В.Янушевскис, А.Г.Мельников, А.Ф.Бойко „Методика оптимизации формы элементов механических систем проектируемых средствами CAD/CAE: промышленные примеры”, Труды 5ой международной научно-технической конференции „Современные проблемы машиностроения”, 23-26 ноября 2010, Томск, Российская Федерация, стр.524-530. (VINITI)
10. Boiko A., Boiko I. „Влияние сварочных ремонтных работ на прочность рамы вагона-цистерны”, Proceedings of 7th International Symposium „Surface Engineering. New Powder Composition Materials. Welding”, 2nd Part, 23-25 March 2011, Minsk, Belarus, pp. 233 - 239.
11. Бойко А., Бойко И. “Влияние ремонтных сварочных работ на срок службы вагона-цистерны”, 10th International Scientific Conference NOMATEX-2012, 12-14 September 2012, Minsk, Belarus, pp. 300-303
12. A.Boiko “Determination of resource reducing a of tank wagons on the Latvian railway due to fatigue damages”, the 1st Congress of World Engineers and Riga Polytechnical Institute / RTU Alumni
13. Vladimir Gonca, Svetlana Polukoshko, Yurij Shvab, Aleksandrs Boiko, “Multilayers spherical control hinge characteristics optimization”, 11th International Conference Vibroengineering 2012, 11-12 October 2012, Kaunas, Lithuania, 8 p., Vibromechanika. Journal of Vibroengineering, (SCOPUS) (In press).

14. Janushevskis, A. Melnikovs, A. Boyko “Shape Optimization of 3D Mechanical Systems Using Metamodels”, 2013 International Conference on MEMS and Mechanics (MEMSM 2013) 15-16 March 2013, Wuhan, China, in Journal Advanced Materials Research Vol. 705, (2013), pp. 429-435, Trans Tech Publications, Switzerland, ISSN: 1022-6680, (SCOPUS).
15. Janushevskis A., Melnikovs A., Boiko A. Dzelzceļa vagonu cisternu balsta fasonķepu formas optimizācija. Scientific Journal of RTU: Transport and Engineering. Series 6. Riga: Riga Technical University. 5 p. (In press).

Amount and structure of Doctoral thesis

Doctoral thesis consists of introduction and 7 sections, conclusion with main results and conclusions, ten appendices and bibliography (76 titles). Total amount of research is 175 pages in printed form with 147 illustrations.

Short description of research

In first section was performed operational analysis of freight wagon loading of Latvian Railway, in result of which the most loaded appeared tank wagons, for which ones the data on decoupling for regular repairs was collected. Summarized data on damages of four-axle tank wagon frames and boilers [24], by boiler corrosion rate depending on type of transportable cargoes [25], by defect types of material and metal connections [LVS EN ISO 5817] and by quality control types of welded joints [14,15,16] during operation and in warranty intermediate repair period (Fig. 1).

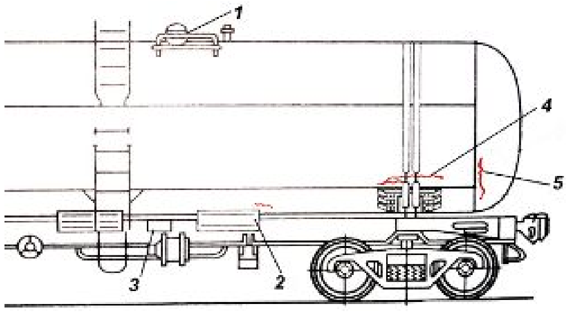

Fig. 1. Zones of tank wagon boiler damages: 1. – welded joints of hatchway; 2 – welded joints of pads; 3 – welded joints of discharging device; 4 – welded joints of boiler edge ring at sill supports; 5 – welded joints of bottom.

Performed review and analysis on recent researches, performed by series of authors from leading research institutes and universities, on assessment of remaining resource of freight wagons [26-30].

Estimating of the remaining resource existence by the formula, using the data about thickness which can be found in the documentation leads to significant mistakes in calculations. Remaining resource can be determined taking into account the oil companies' requirements which being formulated using the existing data about materials and transporting goods influence to the wear of corrosion [43-52]. Remaining resource can be determined in simplified manner by wear of corrosion or total run data, on the base of metal impact viscosity assessment [28] or taking into account the economic efficiency of planning repair [42].

However, more efficient way is to determine load, which cause damages and their frequency in operation (Fig. 2a) [30], then to select rule of load distribution and, by performing impact assessment of this or other load and its reoccurrence in specific construction node, according to which the resource calculation can be performed, basing on single loads, repeated loads up to 10^5 cycles (low-cyclic loading) and more than 10^5 cycles (high-cyclic loading).

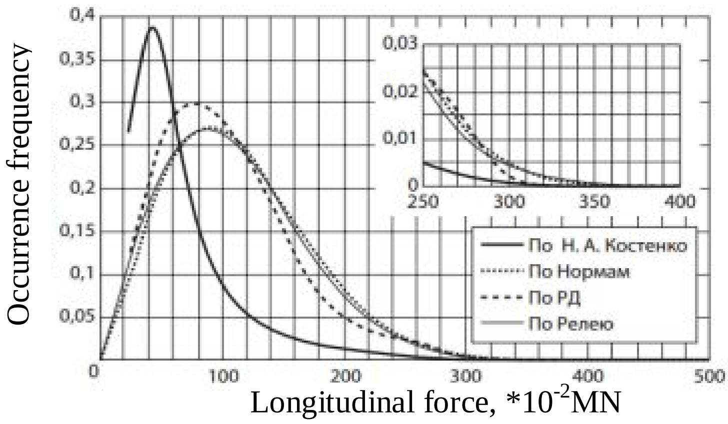

Fig. 2a. Distribution of longitudinal forces by data of Standards [1], what impact freight wagons during operation, comparison with other distribution types and in comparison with Relay distribution

To determine reoccurrence of existing load regimes there is used also analysis of movement velocity reoccurrence in operation (Fig. 2b) [31] with usage of the following Log-normal law of Veibul's rule to describe reoccurrence distribution of stabilizing loading regime.

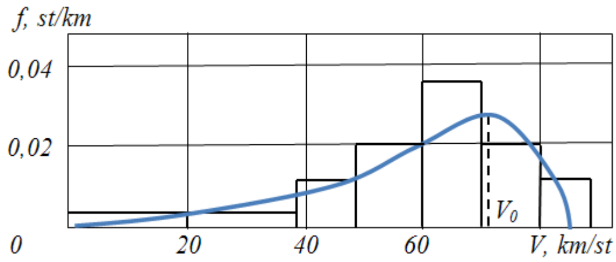

Fig. 2b. Density distribution of possible velocities of freight wagons

Mechanical damages and occurrence of cracks generally are described with Vaibul's distribution rule [40].

In nowadays, according to valid Regulations on life time extension of freight wagons and refrigerator wagons [5] scientific centre "Vagoni" and other similar centres have elaborated and apply methodology of technical diagnostics and assessment of possibility to extend life time [41] in the following amount:

1. Inspection of technical condition, by taking into account operational conditions, which include in themselves also thickness measuring of basic load-bearing elements of wagon constructions.
2. Intensity assessment of wagon operation.
3. Statistic calculation of ultimate elements taking into account decrease of thickness operation in relation with corrosion and wear to find more loaded elements of construction node.
4. Tests of inspected wagon group control.

Performed analysis of valid standards – technical documentation [1,3,5,6,8,32-35] what regulates procedure for remaining resource assessment through performance of resource impact tests.

The methods of fatigue strength assessment according to the Russian Federation Ministry of Transport of railway rolling stock with rail gauge 1520 mm normative documents [1] and the European standards [53] and the manual "FKM-guidline Analytical strength assessment" [54]. were compared.

In result of performed analytical review the aim of research was set:

Aim of research: to examine exposure of tank wagons with expired life time to damages, and to examine repair quality with purpose to elaborate analytic determination methodology of tank wagon remaining resource at cyclic loading to increase operational safety of tank wagons in warranty intermediate repair period.

Performed analytic review allows making the following conclusions:

- Because tank wagons are the most loaded and they transport dangerous cargoes, towards them are established increased requirements, thereby four-axle tank wagon for transportation of petroleum products, for which the appropriate remaining resource assessment at cyclic loading was performed, is selected as research object in Doctoral thesis.
- Strength of load-bearing tank wagons with expired life time in planned repairs is renewed according to Repairs instruction [3], however fatigue cracks appear again in warranty intermediate repair period. Number of decoupling wagons from trains for sending to regular repairs due to discovered damages in recent years increases. Thereby it is required to increase performance quality of planned repairs.
- During operation corrosion rate of boiler depending on transportable cargo can change from standard meaning 0.05 mm annually up to by 0.5 mm annually.
- In order to successfully diagnose various damages of welded joints of boiler and frame and material defects in joint area, it is needed to select efficient control type for welded connections.
- According to performed review on usable methods for remaining resource determination of constructions, it is required to select more efficient assessment method of tank wagon remaining resource for each zone of damages separately, taking into account the size of loading and frequency of reoccurrence, what cause fatigue damages in these zones.
- In result of analysis of valid documentation [1,3,5,6,8], which was elaborated before several decades with the following supplements and test results, performed according to standards of calculated loading regimes [1], was clarified that according to this documentation the damages, which appears to wagons with expired life time, are not discovered. So, it is required to elaborate proposals and supplements for valid documentation to create new methodology for determination of remaining resource for tank wagons with expired life time at cyclic loading.
- Assessment of remaining resource will be possible if causes, why the damages appears during intermediate repair period will be discovered, and supplements for methodology of tank wagon diagnostics with purpose to determine remaining strength of load-bearing elements for constructions will be elaborated.

In second section the statistical analysis for damages of 374 tank wagons was performed. Tank wagons were operated in conditions of Latvian Railway. Tank wagons were manufactured from 1964 to 1980, so they are into operation from 29 to 46 years. Fleet of tank wagons according to SJSC Latvian Railway includes four-axle and eight-axle wagons. On 2012 their total amount was 1216 (see Table 1). Life time for tank wagons is **32** years. According to regulations of repair system period of intermediate repairs is 3 years (after DR repairs) and 8 years (after KR repairs).

Table 1

No.	Indicators	1990	1995	2000	2005	2006	2007	2008	2009	2010
1	Wagons, in disposal of railway*	10729	10140	7326	5290	5225	5256	5228	6043	6038
2	including: covered	1956	1586	1398	1327	1308	1294	1288	1589	1589
3	platforms	992	1090	883	97	95	74	74	74	74
4	semi-wagons	1883	1767	1462	1183	1163	1138	1125	1125	1121
5	tank wagons	2325	1813	1311	1222	1220	1219	1217	1217	1216 **and to 2012**

From them 1063 – for-axle, and 153 – eight-axle wagons. The most common models of four-axle tank wagons are:

“15-1443” - 671 wagons (and models “15-1443-80” - 42 wagons with KRP),

“15-Ц863” - 152 wagons (and models “15-Ц863” - 91 wagons with KRP).

Among eight-axle tank wagons the most common are the following models:

“15-871-6” - 107 wagons (and models “15-871” - 6 wagons).

“15-1500” - 42 wagons.

Existence of damages was inspected for 309 tank wagons of model “15-1443” and 55 tank wagons of model “15-Ц863”, as well as 10 tank wagons of model “15-871-6”. Operational time of wagons was from 29 to 46 years. Number of inspected tank wagons of total tank wagons, which are in freight fleet of SJSC Latvian Railway, is illustrated in Table 2.

Table 2

No.	Model	Number of wagons in fleet	Number of inspected wagons	Proportion of inspected wagons,%
1	15-1443	671	309	46
2	15-Ц863	152	55	36
3	15-871-6	107	10	9

Statistical analyses, performed after discovered damages in three tank wagons, were obtained data on distribution of damages of tank wagon boilers and frames in descending order according to importance of defect. Number of damages by years is shown in Table 3. Types of discovered damages are graphically illustrated in Figure 3.

Table 3

Operation time, year	Number of damages in total	Number of wagons by years	Number of damages per one wagon
1	2	3	4
29	24	6	4.00
30	104	37	2.81
31	64	26	2.46
32	121	50	2.42
33	134	50	2.68
34	129	49	2.63

Operation time, year	Number of damages in total	Number of wagons by years	Number of damages per one wagon
1	**2**	**3**	**4**
35	118	40	2.95
36	82	27	3.04
37	59	21	2.81
38	57	25	2.28
39	57	17	3.35
40	12	41	0.29
41	25	8	3.13
42	7	2	3.50
43	3	1	3.00
44	6	1	6.00
45	0	1	0.00
46	2	1	2.00

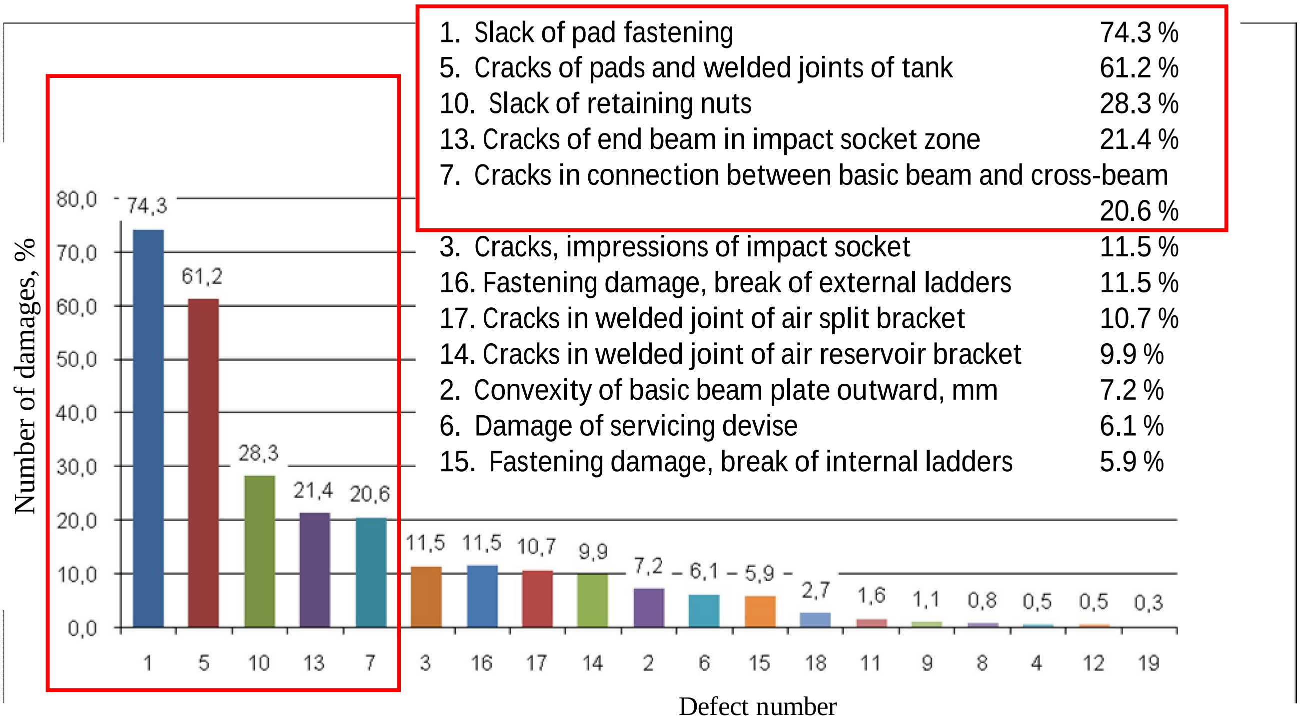

Fig. 3. Distribution of damages towards total number of inspected batch of wagons in amount of 374 tank wagons

Obtained regularities of damage distribution in total amount of four-axle tank wagons and for individual damages of tank wagons allow to assess time of defect occurrence in pads of tank wagon boilers, and to predict their occurrence in the next intermediate repair period (see Fig.4).

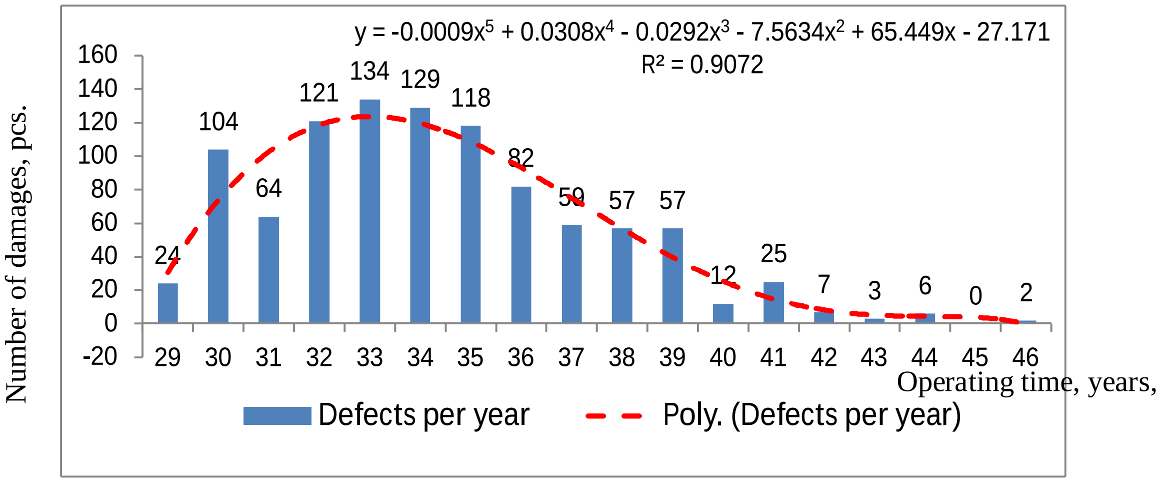

Fig.4. Distribution of damages in tank wagon sample depending on operating time

Processing results of operational damages discovered that main defects of tank wagon boiler and zones of their occurrence are:

1. Slack of pad fastening;
2. Zone of pads – formation of cracks in places, where they are welded to tank wagon boiler;
3. Slack of retaining nuts.

Tank wagon frame has the following main defects:

1. Cracks of impact socket in end beams.
2. Cracks in connections between basic beam and cross-beams.

Performed assessment of currently valid repair system [36,37], in result of which was discovered that annual depot repairs decreases damage flow more efficiently in the following zones:

- Slack of pad fastening (see Fig.5).
- Cracks of impact socket in end beams.

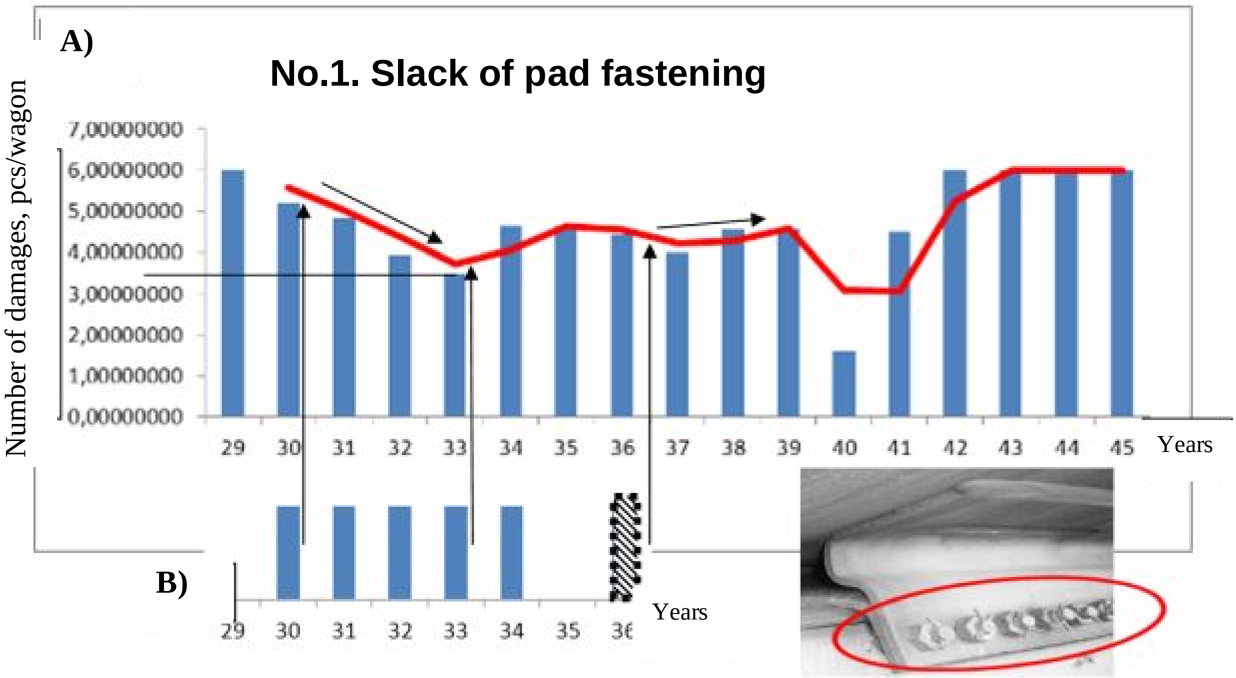

Fig.5. A) Total amount of slacks of pad fastening defects; B) Performance scheme of depot repairs in operational years of tank wagon 30, 31, 32, 33, 34, and performance scheme of capital repairs in year 36

Equal, not too explicit impact of annual depot repairs and capital repairs to decrease of damage occurrence was discovered for the following damages:

- Slack of boiler nut;
- Joints, where pads were welded to boiler

Obtained results on operation in Latvian Railway can be referred also to other one-type wagons, which are operated in similar conditions.

In third chapter is created model of ultimate elements of tank wagon boiler and frame (Fig.6, 7) and determined zones of increased stress.

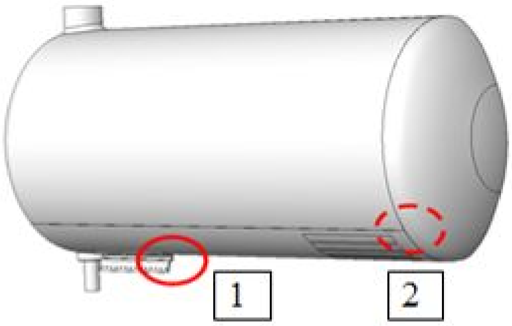

Fig.6. Calculation model of ¼ boiler: 1- welded joints of pads, 2 – connection of T-type joints

In result of boiler strength calculation according to Standards [1] maximal equivalent stresses occur in the following zones:

- Lower plates of boiler edge ring at pads.
- Lower plate of boiler edge ring and bottom of boiler.
- Sill supports at boiler edge ring.
- Hatchway.

According to normative calculations **boiler** strength in zones 2, 4, 5 (see Fig.1) satisfies condition of sufficient strength (Table 4).

Table 4

Zone No, title	Stress MPa	
	Regimes	
	First	Third
2 Pads	208	99
5 Bottom	146	89
4 Sill supports	101	60

In result of **frame** strength calculation by loading basic regimes according to Standards [1] maximal equivalent stresses occur in the following zones:

1. Upper and lower plate of basic beam in connection with cross-beam – First compression regime – 220 MPa,
2. Upper plate of cross-beam in connection with basic beam – First compression regime 197 MPa,
3. Upper plate of basic beam before lath of frame – Third compression regime – 85 MPa;
4. Vertical plate of cross-beam in connection with basic beam – Third compression regime – 71 MPa;

Location schemes of calculation points and increased stresses are shown in Figure 7.

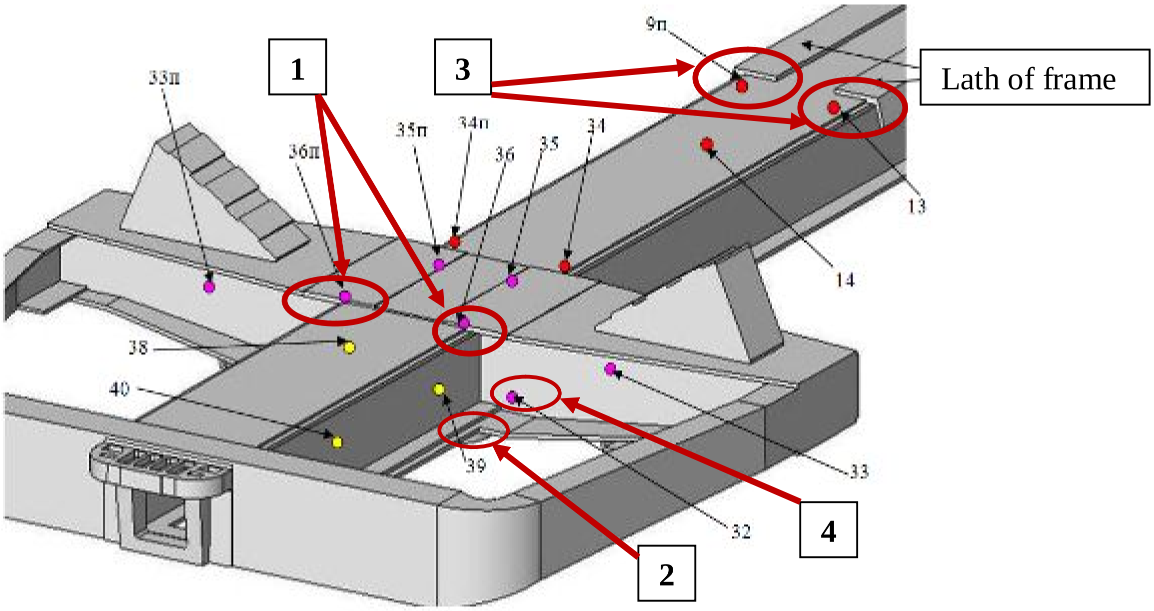

Fig.7a. Location of calculation points of frame, view from top, turned

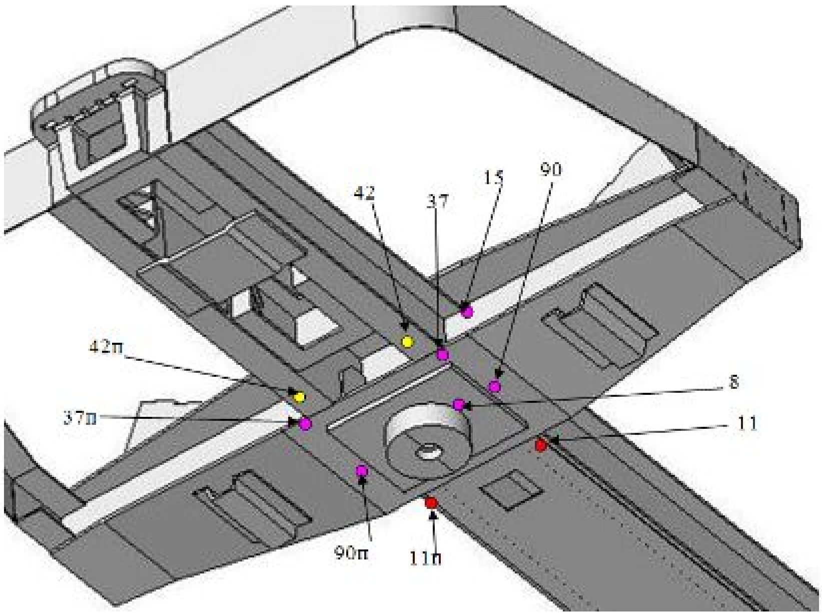

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Fig.7b. Location scheme of maximal stress points in distance of 20-25 mm from stress concentrators, view from bottom, turned

So, in result of analysis of stress state were discovered causes damages in tank wagon load-bearing elements:

- In tank wagon **boiler**:
  1. in zones of welded joints of hatchway, in zones of welded joints of discharging device – load with test pressure and in first regime;
  2. in zone of welded joints of pads – first regime load and hydraulic freight impact load;
  3. in zone of welded joints of boiler edge ring at sill supports – first regime load;
  4. in zone of welded joints of bottom – first regime load and load with test pressure.

- In tank wagon **frame**:
    1. Upper and lower plate of basic beam in connection with cross-beam – compression, first regime load,
    2. Upper plate of cross-beam in connection with basic beam – compression, first regime load,
    3. Upper plate of basic beam before laths of frame – compression, third regime load,
    4. Vertical plate of cross-beam in connection with basic beam – compression, third regime load.

In fourth section

1. Performed analysis of loaded state according to elaborated calculation models, determined loads, which create the biggest stress in boiler damage zones. Calculations were performed for:
    1. factory performance,
    2. in presence of damages,
    3. in repaired state after restorative repairs.
2. Discovered that by performing repairs in zone of pads, it is required to control length of perpendicular joint, which should be located in range of 100 mm – 150 mm (from projection line of longitudinal joints - - - - - in splits of middle part of pad on line of perpendicular joint).

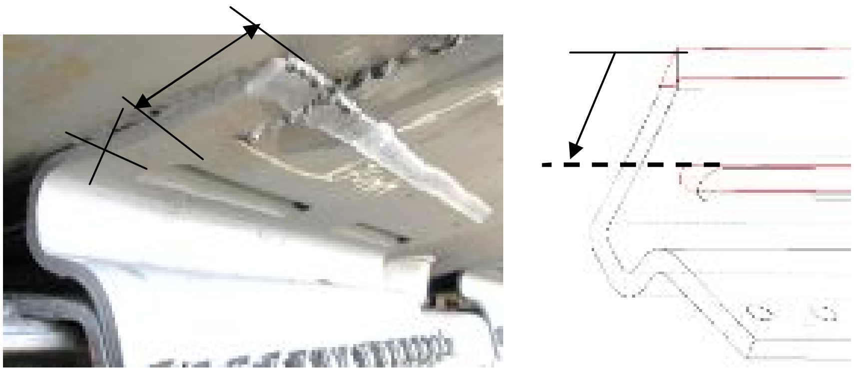

Fig.8. Crack in perpendicular joint of tank wagon pad and model

3. Discovered that by performing repairs in zone of sill supports, it is required to control joining of sill supports to boiler edge ring. In boiler calculations also uneven basing on sill supports should be taken into account (see Fig. 9), because in given case calculated stresses in zone of boiler edge ring exceed limit of material changeability, which leads to occurrence of deformation at boiler edge ring and proves occurrence of welded joints in zone 4 and 5 (see Fig.1, Table 5) during operation.

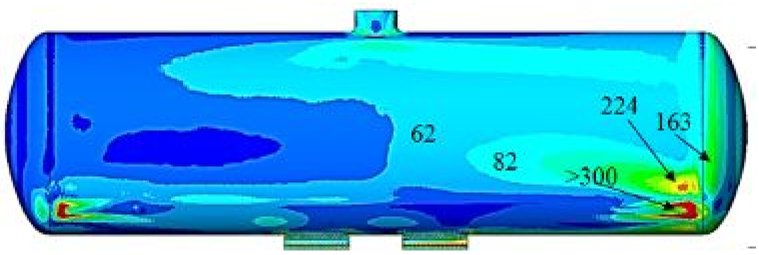

Fig.9. Equivalent stresses in boiler support on upper sill supports, view from side

Table 5

Zone No., title	Stress, MPa $1^{st}/3^{rd}$ regime		
	By standards [1]	Sinking of supports	Increase
2 Pads	208\99	240\110	32 \ 11
5 Bottom	146\89	163\103	17 \ 14
4 Supports	101\60	224 \ 130	123 \ 70

4. So, in result of analysis of four-axle tank wagon damages there were determined basic beams and cross-beam in basic zone in connection, where cracks occur:
- connection of upper and lower shelves of basic beam and cross-beam;
- connection of vertical plates of cross-beam with upper and lower shelves of cross-beam.

5. In result of strength calculation of variants it was determined that crack creation zones are stress concentrators. Calculated stresses in connection do not exceed allowed limits at maximal compression loads in first normative regime. Creation of defects (deep cracks, bumps, fragments, which were broken off) in these zones leads to increase of stresses by 2.7…3.5 times, in results stresses can exceed the yield strength.

6. Non-qualitative welding during repairs, when end of welded joints are located in zones of stress concentrations, leads to increase of stresses up to 53 %.

7. Non-optimal shape and thickness of fastening plates, as well as incorrect location of plates cause inefficient decrease of stresses, but at end part of plates the stresses increased by 3…5 times with formation of new concentration zones of stresses.

8. Proposed calculated fastening plate with truncated shape decreases stresses in 2 times in zone of basic beam and upper shelves of cross-beam, and does not form new concentration zones of stresses. However, usage of modelled fastening plate in zone of upper shelves is not sufficient; fastening plate should be elaborated also for connection of lower shelves.

9. Discovered cause of damages in connection zone of vertical plate of tank wagon cross-beam with basic beam. In result of calculations of tank wagon lateral swinging regime there were determined zones of maximal equivalent loading at connection of basic beam and cross-beam, marked in Figure 10. From obtained results it can be concluded that stress sweep is maximal in point 35 and it decreases in points 36, 32, 7, 90. So, it is required reoccurrence of these stresses, and to calculate remaining resource for given zone.

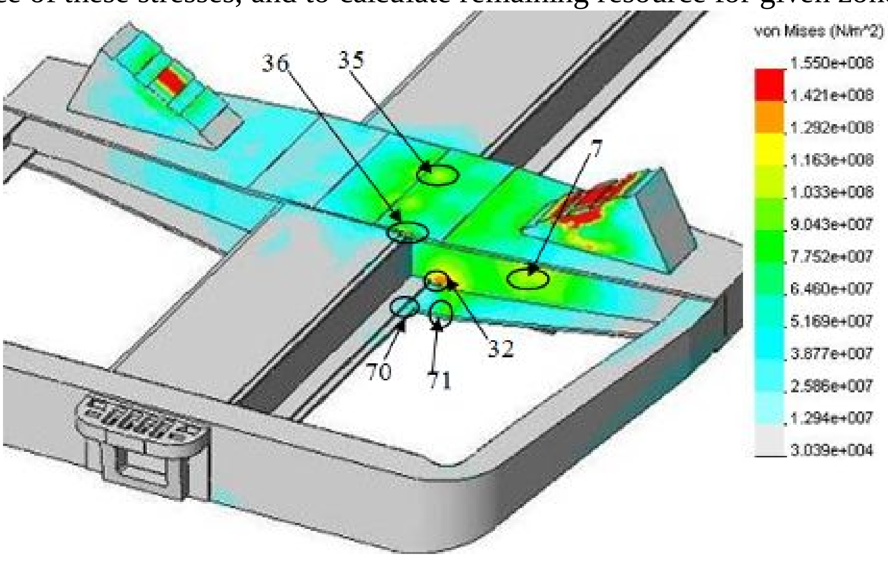

Fig.10a. Distribution of stresses in left support loading, view from top

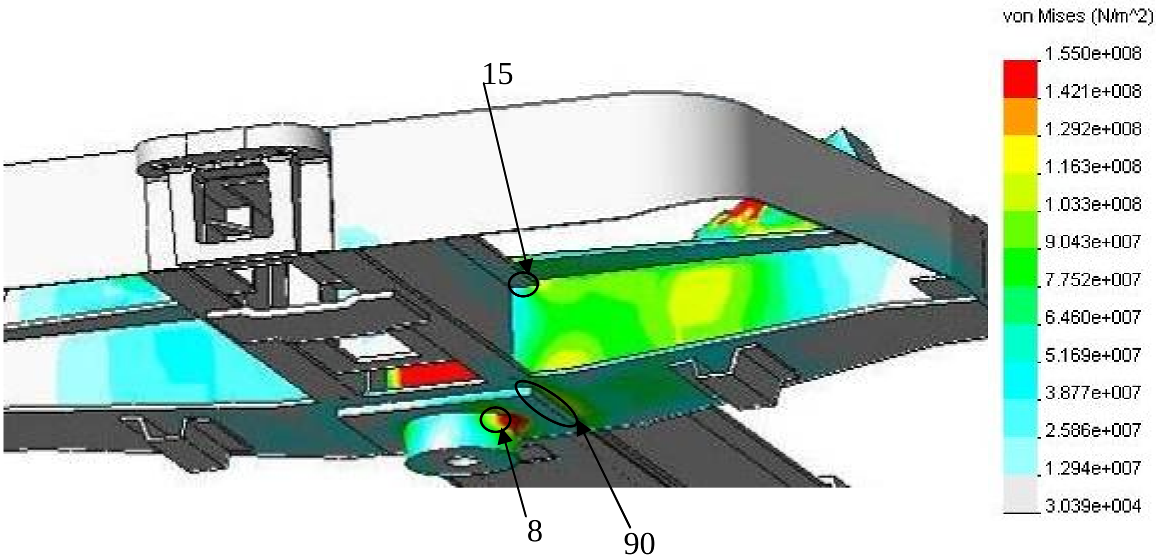

Fig.10b. Distribution of stresses in left support loading, view from bottom

According to paragraph 2.2.3 of Standards [1] lateral swinging regime for nodes of frame cross-beams is taken into account by increasing vertical dynamics calculation coefficient by 20%. However, as calculations show, increase of dynamic coefficient by 20 % does not take character and size of changes of stress in connection zone between basic beam and cross-beam into account completely.

In fifth section was selected and justified method for determination of tank wagon remaining resource by 2 criteria:

1. After destruction from one individual impact (extreme load);
2. After accumulation of remained deformation.

Depending on load and its re-occurrence for each fatigue damage zone was selected remaining resource assessment method and determined minimal meanings of it.

Discovered impact of repair works quality to remaining resource of tank wagon load-bearing elements at high-cyclic (cyclic) loading. So, if length of perpendicular welded joint reaches width of pad, average life time of this node decreases up to 1.81 year, which is less than warranted intermediate repair period (3 years). So, according to calculation according to rule of normal distribution law 97 % (1.81 year) of tank wagons it is possible formation of cracks in end of welded cross-beam of pads during intermediate repair period (see Fig.11), which is less than warranty intermediate repair period (3 years) and less than calculation period (5 years), which is performed according to methodology of remaining resource assessment.

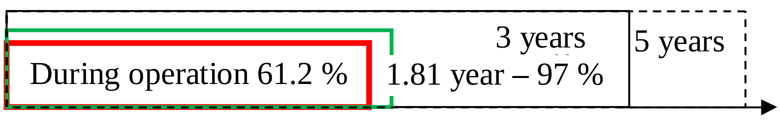

Fig.11. Resource of tank wagon calculations and operation, and term of warranty intermediate repairs

Calculation results complies with results of statistical researches, which were performed in Fig.3, according to which ones the defect was discovered in 229 of 374 tank wagons of inspected batch, which comprises 61.2 %.

Difference of proposed calculation method of remaining resource determination in accuracy, comparing with operational data on damages in zone, when pads were welded to boiler edge ring, is 36 %. In comparison with test data, calculation methods for remaining resource determination, are closer to operational results. Life time period, which was determined according to Depot methodologies substantially differs from operational data.

In accordance with the known optimization methods, where it is offered to use different realizations of so-called homogenization method [55] and resource-saving technique of shape optimization [56] in Doctoral thesis optimization by weight minimisation of shape of the frame pads in zone of perpendicular joint is performed [9], it has decreased the stress by 21 % (till 190 MPa). There is known method [38], according to which it is proposed to put the patch with increased length under each pad of the frame. When length of patch increases by 30-40 mm, stress decreases by 40 %, but the stress level remains high (265 MPa), and it is increasing weight and operational capacity.

Performed shape optimization at pads of mass minimization [18] in zones of perpendicular joints, which decreased the stress by 27 %. Performed shape optimization of fastening repair plates in console part of tank wagon frame. Proposed type of fastening with plates with concave shape edges decreases stress level more than 2 times (Fig. 12) in connection with upper connecting plates of basic beam and cross-beam, at the same time by smoothing previously existed stress concentrators.

Methodology of shape optimisation was approbated on the base of optimisation of measurable disk shape of pair of wagon wheels [19,21,23].

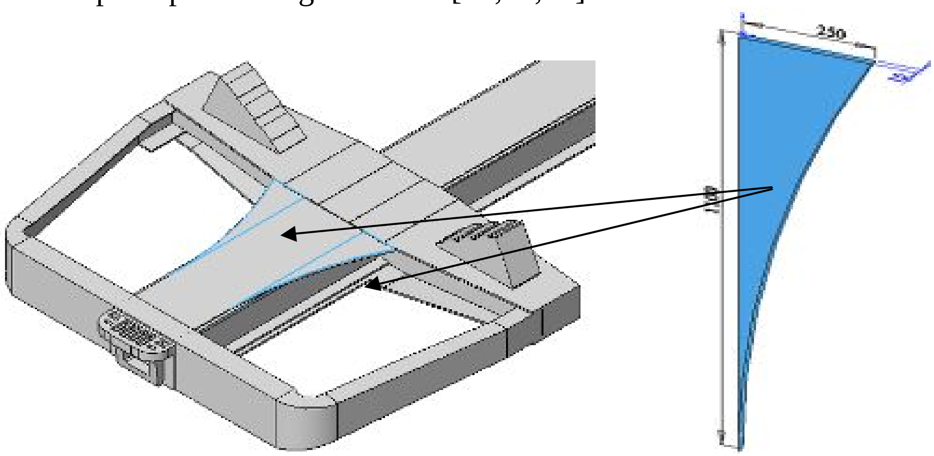

Fig.12. Console part of tank wagon frame

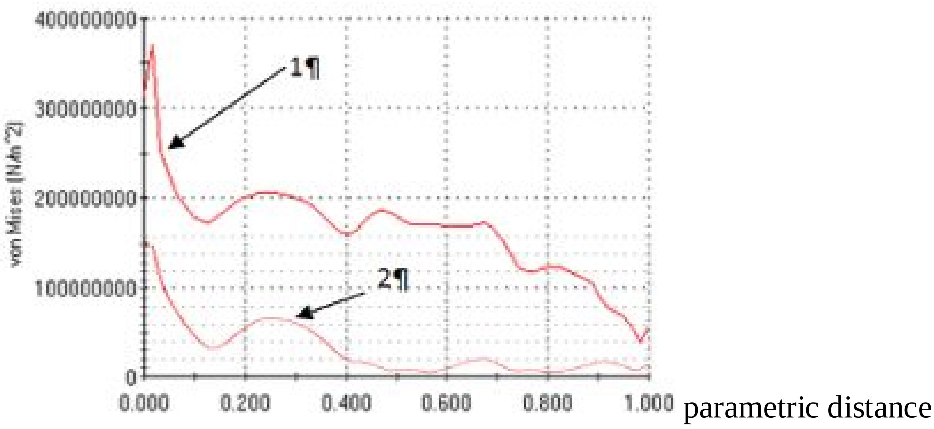

Fig.13. Comparison of frame stresses (strengthening plates in concave external edge) before and after strengthening. 1 – stresses of frame before strengthening, 2 - stresses of frame after strengthening.

Proposed type of fastening with plates with concave shape edges (see Fig.12) decreases stress level more than 2 times (see Fig.13) in connection with upper connecting plates of basic beam and cross-beam, at the same time by smoothing strain concentrators.

Given recommendations [14-16,39] on organization and surveillance of welding works, by performing repair types for tank wagon renovation.

In sixth section for results of damage analysis and performed strength calculations and results of remaining resource assessment was discovered zones of fatigue damages with the more frequent reoccurrence in conditions of SJSC Latvian Railway. For performance of diagnostics with purpose to determine remaining strength and resource, was proposed the following map for measurements of remaining thicknesses of boiler (see Fig.14) in zones of potentially high stress and low resource, discovered in way of calculations. Highlighted "**O**" zones were marked in places, where damages occur most often. Inspection zones, performed with purpose to discover existence of damages, are shown with arrows. Digits in frames reflect intensity of damage occurrence in descending order from 1 to 5, but lines, which connect frames, reflect mutual impact of damages.

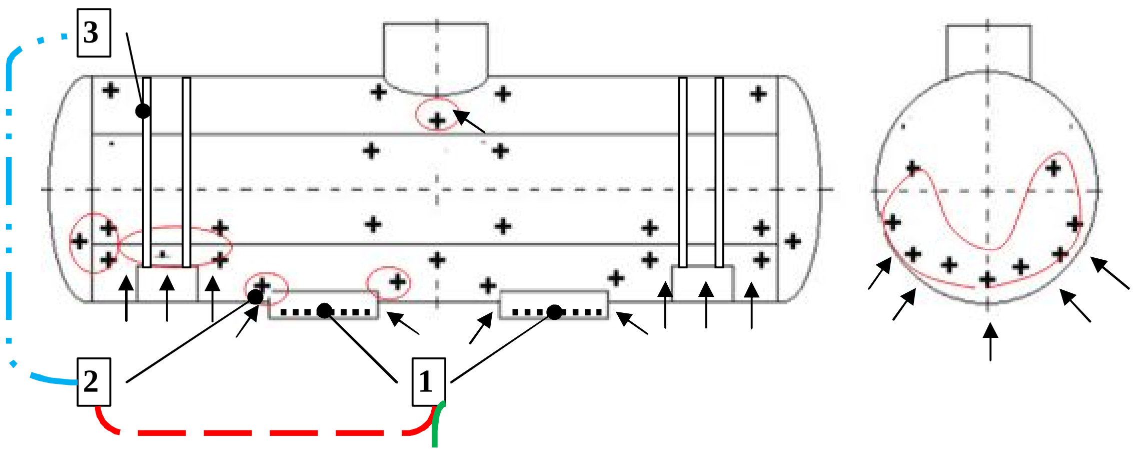

Fig.14.a. Map of inspection zones for boiler thickness measurements and damages

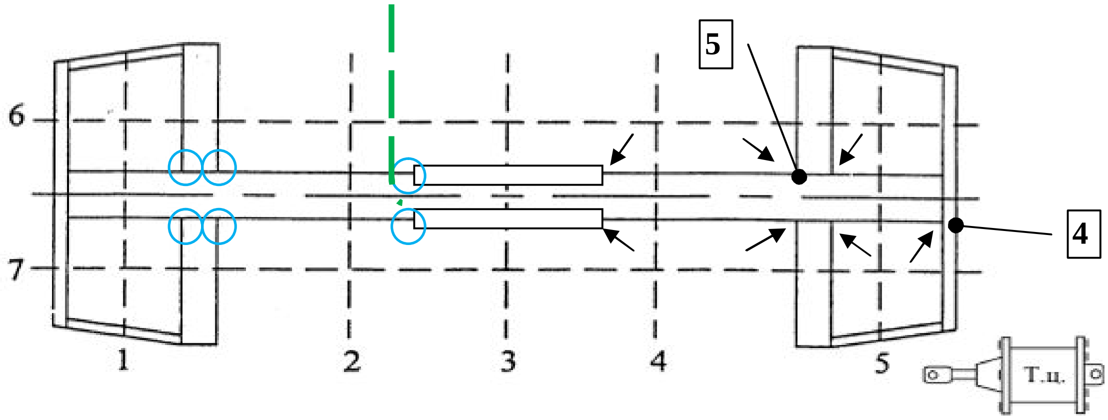

Fig.14.b. Map of inspection zones for frame thickness measurements and damages

Elaborated supplements for tank wagon diagnostics methodology allow discovering fatigue damages of tank wagons more accurately. To ensure data collection and following assessment and calculation of wagon stress, as well as assessment of remaining resource, it is required to collect data in centralized manner in all operational sites.

It is offered to supplement reference 2653 (on performable repair works) and table of damage codes, traffic forms 1354 on exit from repairs, electronic data base of Engineering Computer Centre of Railway Administration with information on fatigue damages of tank wagon load-bearing elements (boiler and frame), after performance of planned repairs and inspection of tank wagons, which are running in international traffic.

Elaborated supplements and proposals will allow discovering fatigue damages of tank wagons more efficiently and substantially will decrease time, which is required for their diagnostics.

In seventh section was elaborated methodology for assessment of remaining resource for four-axle tank wagon at cyclic loading. In methodology there are taken into account the results of created models of four-axle tank wagon frame and boiler ultimate elements and results of created calculation programmes, with assistance of which ones are discovered additional stress regimes, which form fatigue damages in row of tank wagon zones. Taking into account these regimes and discovered zones with low remaining resource, the diagnostic methodology for tank wagons was supplemented and inspection maps were elaborated. On the base of obtained results was formed calculation method for remaining resource of tank wagon at cyclic loads in operational conditions of JSC Latvian Railway.

Calculation results of remaining resource rather accurately reflect operational data and, in fact, confirm them, what allowed to elaborate 4 proposals for specification of normative documentation (Appendix A1).

Assessment methodology of remaining resource

Selection of method for remaining resource calculation:

1. For loads, substantial by size, with low frequency (rarely encountered in operation), the resource should be calculated for case of one impact loads.
2. If there operate loads, which cause damages in tank wagon frame and boiler with number of reoccurrence $N<10^5$, then resource calculation should be performed according to criterion of law-cyclic fatigue.
3. If reoccurrence of variable loads is in range from 10^5 to 10^7, then resource calculation should be performed according to criterion of high-cyclic fatigue.

1. Resource calculation of tank wagon load-bearing elements in case of rarely operating big loads

For loads, substantial by size, with low frequency (rarely encountered in operation), the resource should be calculated in the following manner [22,31]:

Mathematical expectations of impact number $\bar{n}$ up to occurrence of load-bearing elements is determined by simple regularity $\bar{n} \approx 1/p$, where p – probability for impact, at which the stress in any load-bearing element will exceed temporary strength limit. At known function of distribution of operating forces P this probability is $p = 1 - P_i$, where P_i value of distribution function for values of forces, when operating stresses do not exceed allowed limit. By knowing amount of impacts per year, the resource can be assessed in approximate manner according to this criterion.

According to normative calculations stresses are determined bigger ones from maximal load, which cause damages. Then is selected type of distribution, which characterises distribution of forces in more detailed manner, what cause damages. Because Relay distribution describes distribution of compression forces in more accurate manner (Fig.1.8), it is determined by using this distribution:

$$S=(\sigma * P_{Rellaja})/N_{2.5} = ... MPa, \quad (1)$$

where σ – calculation stresses in inspected tank wagon zone, $P_{Rellaja} = 0.88\ MN$ - Relay parameter [31], $N_{2.5}$ – maximal calculation load, which cause damages.

Then is determined strength limit σ_b for material and its contained number of distribution standards, i.e. σ_b / S.

Probability for exceeding this level is equal with:

$$p = 1 - \text{Function value of Relay distribution}, \quad (2)$$

then mathematical expectation of number of impacts up to occurrence of damages will be equal with:

$$Mo=1/(1 - \text{Function value of Relay distribution}), \quad (3)$$

what at number of annual compression impacts Ns complies with remaining operational years T:

$$T = Mo / Ns. \quad (4)$$

Calculation formula of remaining resource with application of Relay distribution is the following:

$$T = \frac{1}{\left(1 - \left(1 - e\left(\frac{-\sigma_b^2}{2 \cdot \frac{\sigma_{p1} \cdot S}{N}}\right)\right)\right)} \cdot \frac{1}{N_F} = \ldots . \quad (5)$$

where N – value of annual longitudinal force;

N_F – annual number of longitudinal forces;

σ_b – material strength limit, N/m^2;

σ_p – stress from operating load in calculation zone, N/m^2;

S - parameter of Relay distribution.

2. Resource calculation of tank wagon load-bearing elements in case of large loads with frequency up to 10^5

It is offered to supplement section 2 of valid Standards (Standards for calculation of forces and calculation of regimes) with additional lateral swinging regime, by assessing strength of freight wagon construction [13], i.e. observance of this regime should be mandatory. Proposal for supplementing of Standards is prepared according to example of tank wagon frame calculation in lateral swinging regime, when boiler is based on external sills (Fig.15).

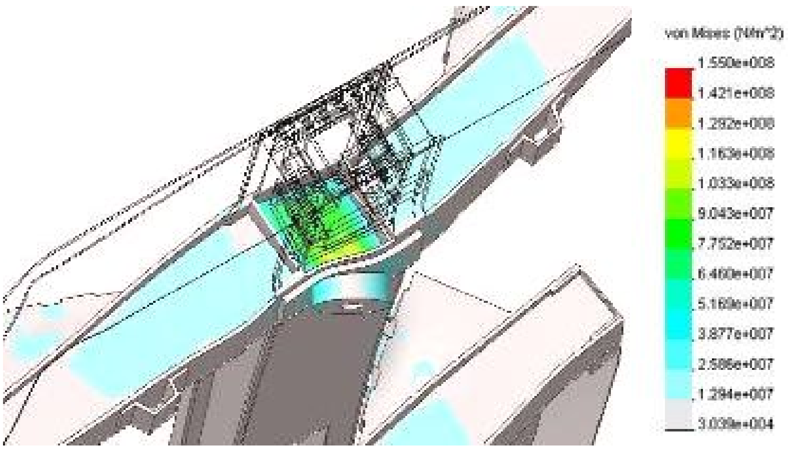

Fig.15. Calculation of lateral swinging regime strength

2.1. Assessment of tank wagon lateral swinging self-frequency

Differential equation of tank wagon lateral swinging self-frequency:

$$I_{O1x} \cdot \beta_x^{''} + \beta_x \left(b^2 \cdot c - P_k \cdot h_{mg}\right), \tag{6}$$

where I_{O1x} – body mass moment of inertia of wagon against longitudinal axle O_{1x}, which is located in plane of axle of wheel pairs;

2b – distance between axles of spring sets;

c – stiffness of springs;

h_{mg} – distance from axle of wheel pairs to centre of gravity;

P_k - body weight with cargo and frame.

After transformation:

$$\beta_x^{''} + \frac{P_k}{I_{O1x}} \left(\frac{b^2}{f_{st}} - h_{mg} \right) \beta_x = 0 . \tag{7}$$

By denoting $\frac{P_k}{I_{O1x}} \left(\frac{b^2}{f_{st}} - h_{mg} \right) = k^2$ equation can be written in following manner:

$$\beta_x^{''} + k^2 \beta_x = 0 . \tag{8}$$

Character equation: $z^2 + k^2 = 0; \; z_1 = ik; \; z_2 = -ik.$

Common solution of differential equation:

$$\beta = C_1 \cos kt + C_2 \sin kt . \tag{9}$$

Derivation:

$$\dot{\beta} = -kC_1 \sin kt + kC_2 \cos kt; \tag{10}$$

Integration constants are determined according to conditions:

$$\beta(t)_{t=0} = \beta_0; \; \dot{\beta}(t)_{t=0} = \dot{\beta}_0; \; C_1 = \beta_0; \; kC_2 = \dot{\beta}_0; \; C_2 = \frac{\dot{\beta}_0}{k};$$

Then

$$\beta = \beta_0 \cos kt + \frac{\dot{\beta}_0}{k} \sin kt; \tag{11}$$

Fluctuation period:

$$T = \frac{2\pi}{k} = 2\pi \cdot \sqrt{\frac{I_{O1x}}{P_k \cdot \left(\frac{b^2}{f_{st}} - h_{mg} \right)}} . \tag{12}$$

Tank wagon lateral swinging self-frequency:

$$f_0 = \frac{1}{T} = \frac{1}{2\pi} \sqrt{\frac{P_k \left(\frac{b^2}{f_{cm}} - h_{mg} \right)}{I_{0_1 x}}}; \tag{13}$$

2.2. Resource calculation of tank wagon load-bearing elements according to criterion of low-cyclic fatigue

Assessment of fatigue strength according to criterion of low-cyclic fatigue should be performed according to the following formula:

$$\frac{[\sigma_{-1k}]^m}{\sigma_{np}} \geq [n], \tag{14}$$

where $[\sigma_{-1k}]$ – minimal fatigue resistance limit of part, what complies to 95 % reliance; σ_{np} – reduced stress amplitude, occurred to regime, which is equivalent for operational regime after damaging activity:

$$\sigma_{np} = 1{,}4 \sqrt[m]{\frac{T\tau}{N_0} f_0 \Gamma\left(\frac{m+2}{2}\right) \sum_{v=0}^{v=v_k} \left(\frac{S_{v_i}}{\varphi}\right)^m p_{v_i}}\ , \tag{15}$$

where

T – calculation life time in years – 32 years;

τ - operation time per year in seconds – determined as proportion of average annual run L towards average speed of wagon in operation V_{av};

m – indication of degree of fatigue curve;

N_0 – base number of cycles;

f_0 – efficient frequency of dynamic load changes in operation;

p_{vi} – time part of operation with speed Vi;

S_{vi} – average square deviation of dynamic loads;

$\Gamma(...)$ – gamma function;

φ – transitional coefficient from asymmetric loading regime at symmetric regime;

$[n]$ - allowable reserve coefficient, *1.8.*

Distribution rules of compression forces [13] and distributions of tank wagon damages in conditions of Latvian Railway with the biggest accuracy are described with distribution density of random variable exponential probability by Relay. Then distribution function is the following:

$$F(x) = 1 - \exp\left(-\frac{x^2}{2 \cdot \sigma^2}\right), x > 0\ , \tag{16}$$

where x – random variable, σ – scale parameter.

Probability density:

$$P(x) = \frac{x^2}{\sigma^2} \cdot \exp\left(-\frac{x^2}{2 \cdot \sigma^2}\right), x > 0\ . \tag{17}$$

Then average time in years up to accumulation of plastic deformation, when crack appears in load-bearing element, can be determined by formula:

$$\overline{T} = \frac{\sigma_{-1}^{m} \cdot N_0}{n_g \cdot 2^{\frac{m}{2}} \cdot \Gamma\left(\frac{m}{2} + 1\right) \cdot S^m}, \qquad (18)$$

where σ_{-1} – limit of fatigue resistance at N_0=10^6 cycles;

n_g – number of compression loads in one operational year.

2.3. Resource calculation of tank wagon load-bearing elements according to criterion of high-cyclic fatigue

Assessment of fatigue strength according to criterion of high-cyclic fatigue should be performed according to the following formula:

$$T_p = \frac{\sigma_{-1}^{m} N_0 \varphi_i^{m} V_{av}}{K_\sigma^m \eta^m 3600\ L_g 2^{\frac{m}{2}} \Gamma\left(\frac{m+2}{2}\right) f_0 \sum_i S_{vi}^m p_{vi}}, \qquad (19)$$

where σ_{-1}^{m} – fatigue resistance limit of part, what complies to 95 % reliance;

N_0 – base number of cycles;

φ - coefficient, which takes into account impact of asymmetry of cycle to fatigue strength;

V_{av} - verage movement speed, km/h;

K_σ - coefficient, which characterize decrease of strength limit of construction in comparison with strength limit of standard sample;

η – reserve coefficient;

m – indication of degree of fatigue curve,

L_g - average annual run, km;

$\Gamma(...)$ – gamma function;

f_0 – efficient frequency of dynamic load changes;

p_{vi} - part of operation with speed v_i;

S_{vi} - average square deviation of dynamic loads (stresses).

If there are not available experimental data, average square deviation of dynamic loads (stresses) S_{vi} is determined according to formulae (in case of vertical loads):

$$S_{vi} = 0{,}52 \frac{\overline{K\partial в}}{\beta} P_{cm}, \qquad (20)$$

$$\overline{K_{\partial в}} = a + 3.6*10^{-4} b \frac{V-15}{f_{cm}}, \text{ if } V \geq 15 \text{ m/sec}; \qquad (21)$$

$$\overline{K_{\partial в}} = a \frac{V}{15}, \text{ if } V \leq \frac{V}{15}, \qquad (22)$$

where a = 0.05 for body elements; 0.1 – for trolley parts with springs; 0.15 - for trolley parts without springs.

Such calculations of complex currently are not intended in valid Standards [1], thereby insufficient strength of tank wagon frame and separate zones of boiler was not discovered during designing process, as well as by performing calculations of remaining resource.

Elaborated methodology allows assessing the remaining resource more accurately with existing information on tank wagon operational damages. Application of elaborated methodology will allow specifying warranty operational terms of intermediate repair and type of regular planned repair, which, in its turn, will decrease costs for unplanned repairs.

To JSC Latvian Railway were prepared and submitted the following proposals:

Proposals on assessment of remaining resource in calculation of tank wagon strength in section 2 of valid Standards [1]

1. It is required to implement methodology for determination of tank wagon remaining resource at cyclic load and additional lateral swinging regime, by assessing strength of freight wagon construction in valid Standards [1]. Lateral swinging regime is offered to be implemented as normative, respectively, its observation should be mandatory.
2. It is required to implement boiler edge ring supporting regime on sill supports (by sinking of central supports) to assess strength of tank wagon construction in valid Standards [1]. Boiler edge ring supporting on sill supports regime is offered to be implemented as additional one.

Proposals on renovation of perpendicular welded joints of pads

It is offered on the base of performed comparative variants of calculations and frequent damages of this zone in operation to implement in paragraph 5.8.40 of section 5.8 (Cisterns) of valid Welding and melting instruction the additional paragraph with requirement to limit maximal length of perpendicular joint of pads. Content of proposed paragraph and supplemented illustration (15) is given below:

c) welding the cracks, def.2, in perpendicular welded joint or in zone of thermal connection of pad with boiler. Length of perpendicular welded joint may not be longer than *100 ÷140 mm, by ending at projection line of longitudinal joints in cuts of middle part of pad in perpendicular joint.*

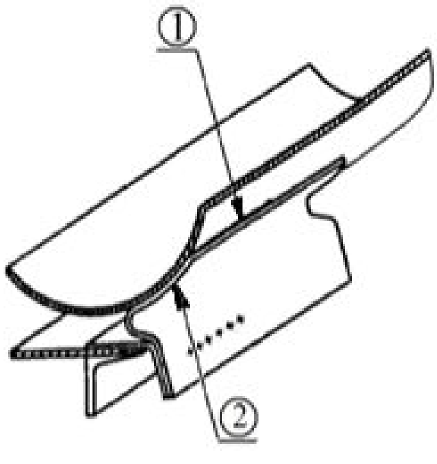

Fig.15. Illustration, supplemented in welding and melting instruction

2 more proposals are prepared for submission in JSC Latvian Railway and given in Appendix A1.

CONCLUSION

1. On the base of analysis of increasing number of regular tank wagon decoupling repairs, review of applicable methods for assessment of tank wagon remaining resource, it is proposed task to elaborate methodology for analytic determination of remaining resource for tank wagons with expired life time at cyclic load to increase operational safety of tank wagons in warranty intermediate repair period.
2. Collected data on statistical processing of damages of tank wagons with expired life time, determined main fatigue damages and their distribution regularities for tank wagon frame and boiler. Determined impact of planned repair system to damage flow.
3. According to models of frame and boiler ultimate elements, formed by author, there were performed strength calculations according to Standards [1] and determined increased equivalent stresses (with do not exceed allowed meanings)
   <u>in boiler</u> in the following zones:
   - in lower plate of boiler edge ring at pads ,
   - in lower plate of boiler edge ring and bottom,
   - basic beams at boiler edge ring,
   - at hatchway;

   <u>in frame</u> in the following zones:
   - upper and lower plate of basic beam in connection with cross-beam – first compression regime,
   - upper plate of cross-beam in connection with basic beam – first compression regime,
   - upper plate of basic beam before plates of frame – third compression regime,
   - vertical plate of cross-beam in connection with basic beam – third compression regime.
4. In result of analysis of stress state there were discovered causes and determined loads which causes the biggest stress:
   - stress with test pressure of first regime and test pressure - in zones of welded joints of hatchway, in zones of welded joints of discharging device,
   - first regime stress - in zone of welded joints of pads – hydraulic freight impact load,
   - first regime stress – in zone of welded joints of boiler edge ring at sill supports,
   - test regime stress and first regime stress - in zone of welded joints of bottom.
5. By performing repairs in pad zone it is required to control length of perpendicular joint, which should be located in zone of pads, it is required to control length of perpendicular joint, which should be located in range from 100 mm to ~140 mm (up to projection line of longitudinal joints in cuts of middle part of pad in perpendicular joint line).
6. By performing repairs in sill support zone, it is required to control how central sill supports join boiler ring. In boiler calculations it is required to take into account uneven basing on sill supports. Taking into account frequent wear and sinking of wooden sill supports, it is required to inspect in further researches the hypothesis wooden sill support – to use in friction node of metal boiler plates self-sliding materials (for example, anti-friction material flubon).
7. Selected and justified method for determination of remaining resource in main fatigue damage zones of tank wagons by two criteria: 1 – after destruction from single impact (extreme loads); 2 – after accumulation of remaining deformations. Resource assessment methods were selected depending on stress value and frequency of its reoccurrence. For each fatigue zone were determined minimal values of remaining resource:

- So, according to high-cyclic fatigue criterion in connection zone of basic beam and cross-beam the resource value in lateral swinging regime consists from 14 to13 years – upper plates of basic beams and cross-beams.
- So, according to low-cycle criterion armour plates and sill support zone in first regime (maximal longitudinal load) and in support on upper sills, if longitudinal length of pads increase, resource comprises 12 years, in armour plate in support zone 15 years.
- Impact of discovered regimes is confirmed with comparative assessment of resource with Normative load assessments and what was attached by author: so, resource decrease in pads comprises 7 years, in boiler supports 199 years.
- In length of perpendicular welded joints of pads, which is equal with width of pad, resource in welded joint decreases up to 1.81 year, in approved intermediate repair period of pad damages occurrence (2-3 years) for more than 97 % tank wagons. Difference of proposed calculation method of remaining resource determination in accuracy, comparing with operational data on damages in zone, when pads were welded to boiler edge ring, is 36 %.

8. Performed shape optimisation of pad in zone of perpendicular joint, which decreased loading by 27 %, for frame plates by 21 %. Methodology of shape optimisation is intended for verified wagon in disc-shape optimization of measurable wheel pair. Proposed fastening king of frame console part in connection of cross-beam and basic beam with curved-shape edge decreases stress level more than 2 times, by smoothing stress concentrators. Methodology of shape optimisation is approbated in disc-shape optimization of measurable wheel pair.
9. Supplemented methodology of tank wagon diagnostics, taking into account damages, which are not included in existing normative documentation, which were discovered in operation in conditions of JSC Latvian Railway. By implementing supplementations and elaborated damage maps with indication to intensity of damage occurrence in descending order, it will be obtained opportunity to assess strength of remaining load-bearing elements with aim to determine remaining resource of tank wagons.
10. Elaborated methodology of remaining resource determination for cyclic loadable tank wagon remaining resource, taking into account discovered additional loading regimes (lateral swinging, outer basing on sill supports). Methodology allows to determine remaining resource of tank wagon in any operational field.
11. According to obtained results of research the following proposals were elaborated and submitted for examination in JSC Latwian Railway: implementation of lateral swinging regime calculation for tank wagon; limitation of maximal length of perpendicular pad welded joints, reference 2653 (on performable repair works) and table of damage codes, traffic forms 1354 on exit from repairs, electronic data base of Engineering Computer Centre of Railway Administration with information on fatigue damages. Proposals were elaborated for submission to authorised wagon management specialists of Railway Administration in Railway transport Commission Council.

Signature: A.Boiko February 2013

SABIEDRĪBA AR IEROBEŽOTU ATBILDĪBU
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RĪGĀ

27.11.2012. Nr. RSSTR-8/181

APLIECINĀJUMS

Apliecinu ka Aleksandrs Boiko 2012.g. novembrī iesniedza SIA „LDZ Ritošā sastāva serviss" izskatīšanai sekojošus priekšlikumus un rekomendācijas:

1. Priekšlikums un papildinājums spēkā esošo Normu 2.sadaļai (Aprēķinu spēku normas un aprēķinu režīmi): piedāvāts ievest kā normatīvo aprēķina režīmu kravas vagonu konstrukciju stiprības novērtējumā papildus šūpošanas režīmu.
2. Priekšlikums un papildinājums spēkā esošā Metināšanas un uzkausēšanas instrukcijas 5.8. sadaļas 5.8.40. punktam: piedāvāts ievest kā normatīvu apakšpunktu „в)" fasonķepu pie cisternvagona katla apmales metinātās šuves garuma kontrole.

Abus priekšlikumus piedāvāts ievest ka normatīvus, t.i. to izpilde būtu obligāta.

Pielikumā:

1. Priekšlikums un papildinājums spēkā esošā Metināšanas un uzkausēšanas instrukcijas 5.8. sadaļas 5.8.40. punktam – 1 lpp.

Datums 27.11.2012

Paraksts

S. Kuļikovs
SIA "LDZ ritošā sastāva serviss"
Tehniskā direkcija
Remonta daļas vadītāja vietnieks

Appendix A1

LIMITED LIABILITY COMPANY
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RIGA

27.11.2012 No.RSSTR-8/181

CERTIFICATION

I confirm that Aleksandrs Boiko in November 2012 has submitted for examination of Ltd “LDZ Ritošā sastāva serviss” the following proposals and recommendations:

1. Proposal and supplement for section 2 of valid Standards (Standards of calculation forces and calculation regimes): it is offered to implement additional swinging regime as normative calculation regime for strength assessment freight wagon constructions.
2. Proposal and supplement for paragraph 5.8.40 of section 5.8 of valid Welding and melting instruction: it is offered to implement as normative sub-paragraph “b”) length control of welded joint of pad at tank wagon boiler edge.

Both proposals are offered to be implemented as normative, respectively, observance of them would be mandatory.

In appendix:

1. Proposal and supplement for paragraph 5.8.40 of section 5.8 of valid Welding and melting instruction – 1 page.

Date 27.11.2012 Signature /*Signature*/

S. Kuļikovs
Ltd. “LDZ ritošā sastāva serviss”
Technical direction
Assistant director of repair department

PROPOSALS FOR SUPPLEMENTATION OF VALID NORMATIVE DOCUMENTATION IN JSC LATVIAN RAILWAY

Prepared and submitted proposals [12] in administration of Latvian Railway for supplementation of Standards [1] for their submission in Dynamic and strength department of rolling stock in Russian Railway Research Institute, as well as there are prepared proposals for supplementation of Welding and melting instruction [3] for its submission to authorised wagon management specialists of Railway Administration in Railway transport Commission Council (now the proposals (see Appendix A1) are in examination of Ltd. “LDZ Ritošā sastāva serviss”). They are the following:

Submitted:

1. It is offered to supplement section 2 of valid Standards (Standards for calculation of forces and calculation of regimes) with additional lateral swinging regime, by assessing strength of freight wagon construction. Lateral swinging regime is proposed to be implemented as normative, respectively, observance of it should be mandatory.
2. It is offered to supplement paragraph 5.8.40 of section 5.8 (Cisterns) of valid Welding and melting instruction with sub-paragraph (c) in relation with length control of welded joint of pad at tank wagon boiler edge ring. Proposal is offered to be implemented as normative, respectively, observance of it should be mandatory.

Prepared:

3. It is offered to supplement valid Standards [1] with additional boiler edge ring reliance on upper sill supports (in case of wear of central supports) to assess strength of tank wagon constructions. Loading regime, when boiler edge ring is based on upper sill supports is offered to be implemented as additional regime.
4. It is offered to supplement reference 2653 (on performable repair works) and table of damage codes, traffic forms 1354 on exit from repairs, electronic data base of Engineering Computer Centre of Railway Administration with information on fatigue damages of tank wagon load-bearing elements (boiler and frame), which should be discovered during operation and before performance of planned repairs. It is offered to collect data on fatigue damages of tank wagons, which are running in international traffic.

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