Nikolay LYSIKOV*, Roman KOVALEV, Gennadiy MIKHEEV
Laboratory of Computational Mechanics, Bryansk State Technical University
bulv. 50-let Oktyabrya, 7, Bryansk, 241035, Russia
**Corresponding author*. E-mail: um@umlab.ru

STRESS LOAD AND DURABILITY ANALYSIS OF RAILWAY VEHICLES USING MULTIBODY APPROACH

Summary. The present paper describes the CAE-based approach for durability analysis that is being implemented in Universal Mechanism software to predict the fatigue damage of parts of mechanical systems. The approach predicts fatigue strength of structural components of machines and mechanisms based on results of simulating their dynamics taking into account real working conditions. An application to the developed software to a stress load and durability analysis is considered.

АНАЛИЗ НАГРУЖЕННОСТИ И ДОЛГОВЕЧНОСТИ ЖЕЛЕЗНОДОРОЖНЫХ ЭКИПАЖЕЙ МЕТОДАМИ ДИНАМИКИ СИСТЕМ ТЕЛ

Аннотация. В настоящей статье рассмотрен подход к анализу нагруженности и долговечности, реализованный в программном комплексе «Универсальный механизм». Предлагаемый подход включает средства комплексной оценки динамических и прочностных характеристик конструкций, основанные на проведении вычислительных экспериментов с математическими моделями исследуемых объектов. Рассмотрено приложение рассматриваемой методики к анализу динамической нагруженности и усталостной долговечности рамы длиннобазной платформы для перевозки крупнотоннажных контейнеров.

1. INTRODUCTION

Designing new railway vehicles and their modernization supposes a complex estimation of their characteristics based on results of a stress, dynamical and fatigue analysis. One of the most effective methods of such analysis is the computer simulation.

"Universal Mechanism" (UM) software[1], which is being developed at the Laboratory of Computational Mechanics of Bryansk State Technical University, Russia, under supervision of Prof. D. Pogorelov, includes tools for dynamical, stress load and fatigue analysis.

UM is a recognized tool for simulation of railway vehicle dynamics [1, 2] which is widely used for simulation of all types of railway vehicles: diesel and electric locomotives, freight and passenger car, as well as special railway machines. The special module for durability analysis was recently developed within UM. The methods that are implemented in this module and an example of its application are the focus of this paper.

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[1] See *http://www.umlab.ru* for details

2. PRINCIPLES

The analysis starts with the dynamical hybrid model in Universal Mechanism. The flexibility characteristics of the structural parts are incorporated into UM model using a modal formulation based upon component mode synthesis. Basically, this method represents the part's flexibility using a modal basis, which is optimized to account for constraint and force locations. The mode shape displacements and stresses are calculated using the finite element programs ANSYS or MSC.NASTRAN.

The durability analysis combines the stress time history information generated during series of numerical experiments in UM and the material fatigue strength characteristics to generate the predicted life distribution in the part.

Any durability analysis relies on three key inputs: stress loading data - time history of the stresses, material data that describes how the material reacts to repeated stress application at various stress levels and parameters of durability calculation method.

By employing the full finite element representation of the component in the UM model, the local stresses are directly obtained as result of the UM solution. Flexible body deformations are modeled as a linear combination of mode shapes. As long as the number of mode shapes selected adequately the modal superposition will model deformations accurately and efficiently.

The idea that the deformation of a flexible body can be represented by the sum of a number of mode shapes, scaled by appropriate factors, can be extended to stresses in the body as well. These factors, or modal coordinates, can be used as the scaling factors on the stress solution of each mode shape and the superposition of these scaled stresses represents the body's instantaneous stress state. If the superposition is performed at every node in the finite element model, for every time step in the UM solution, the stress time history is defined at every location.

The modal coordinate time history can be saved for every numerical simulation. Based on this modal time history and file with orthonormalized mode shapes the stresses at every node can be obtained. When the durability analysis is started, the user is prompted for the location of modal coordinate time history files and orthonormalized mode shapes files, then the type of analysis required and the material data to be used.

With all of the parameters set, durability analysis in UM performs the stress at every node, and then proceeds to multi channel peak/valley extraction and rain flow cycle counting, followed by the damage sum.
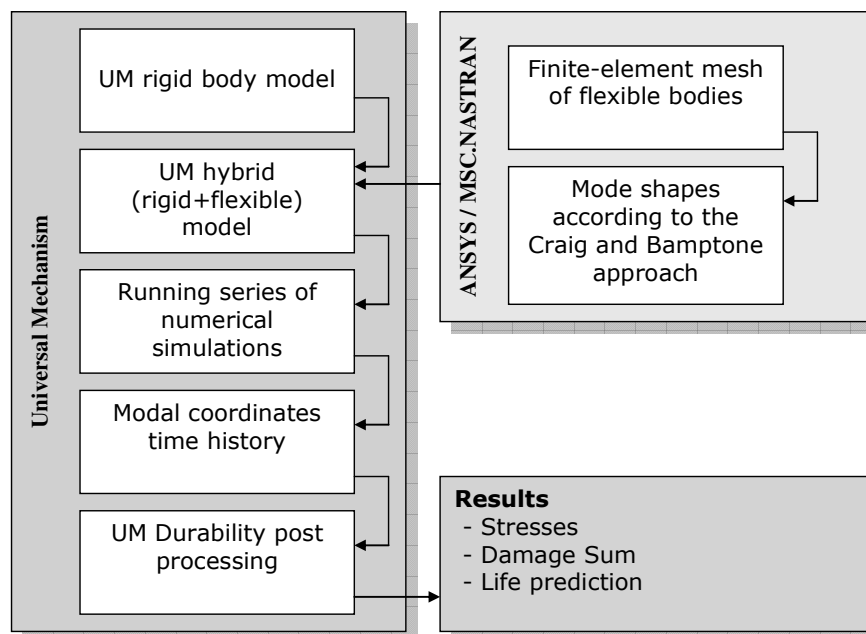

Fig. 1. Workflow in the UM Durability
Рис. 1. Общий порядок работы

3. HYBRID MODELS

Strength analysis of construction is based on using hybrid models which consist of rigid and flexible bodies. The following methods support functioning hybrid models within UM software:
- method of subsystems [3];
- floating frame of reference method;
- finite elements method;
- component mode synthesis method [4].

Equations of motion for calculating flexible displacements are generated with the help of finite element method reference in a local coordinate system. Modal approach is used for increasing the efficiency of simulation. According to the modal approach, flexible displacements are approximated by a sum of static and eigen modes:

$$\mathbf{u} = \sum_j \mathbf{h}_j w_j = \mathbf{Hw} \tag{1}$$

where u is a matrix-column of nodal degrees of freedom of flexible body, h_j is a matrix-column with static or eigen mode, w_j is a modal coordinate which define flexible displacement corresponding to mode with number j, w is a matrix-column of modal coordinates, H is a *modal* matrix.

The main idea of the modal approach is a substitution of a full set of nodal coordinates with a set of modal coordinates. That significantly reduces the number of coordinates of a model, decreases calculation cost during simulation of hybrid systems and keep acceptable calculation precision of strain and stress of flexible bodies at the same time. In applied researches modal approach decreases CPU efforts up to thousand times as compared with the full finite element model and leads to mistake in stress and strain calculation about 5-10%.

Creating a finite element model and calculating modes of flexible body are carried out on prior stage in external FEA software and then prepared data is exported to UM software.

4. DURABILITY ANALYSIS

Using the hybrid models gives us not only a more accurate solution of the dynamical problem but also estimate stress-strain state in flexible parts directly during numerical simulation of vehicle dynamics and save time history at every node of finite-element mesh.

Carrying out series of numerical experiments with various operating condition gives us more or less an appropriate reflection of the stress load and damage of bodies during real operations. The more factors we consider the more accurate results of durability analysis and life prediction we have. Concerning railway vehicle dynamics such series obviously should include various velocity, load (for freight wagons) and railway irregularities. Then stress time histories obtained from these series of numerical experiments are input data for a subsequent fatigue analysis.

The fatigue analysis supposes the stress time history schematization as the necessary step. The schematization represents the time history as a sequence of stress cycles with some calculated parameters. The rainflow-counting algorithm (also known as the "rain-flow counting method") is used in the analysis of fatigue data in order to reduce a spectrum of varying stress into a set of half-cycles with given amplitude and a mean value.

Based on results of rainflow method and using material properties and number of coefficients that describe technological peculiar properties the durability analysis finally calculates damage sum and life prediction of the part.

5. APPLICATION TO DURABILITY ANALYSIS OF A RAILWAY BAY

The developed approach was used for stress load and durability analysis of a newly designed long-wheelbase container railway bay, see Fig. 2. The research was fulfilled in the Laboratory of Computational Mechanics and Department of Locomotives of Bryansk State Technical University, Russia.

Such platforms were designed for container railway transportation from the Far East to Europe and can be loaded with two 40-foot containers. Since such a construction of the bay significantly differs from the standard short-wheelbase bay it was impossible to use for the long-wheelbase bay the same regulations that are used for the standard ones. That is why the numerical simulation was very important. The aim of the research was the estimation of the dynamical properties of the vehicle as well as durability analysis and life prediction.
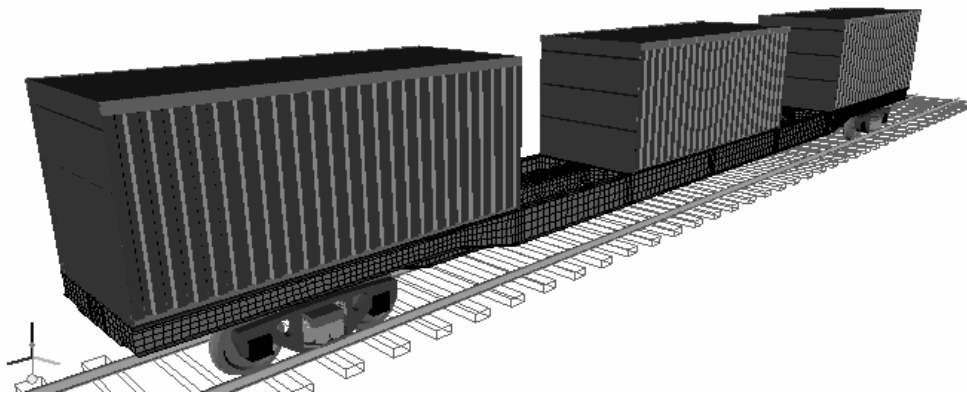
Fig. 2. Long-wheelbase container bay
Рис. 2. Общий вид компьютерной модели платформы

5.1. Stress load analysis

The hybrid model of the bay in UM was developed on the basis of the original technical documentation from the manufacturer. The model of the bay with three 20-foot containers is presented in Fig. 2.

Containers and three-piece bogies are modeled as rigid bodies. The frame of the bay is a flexible body of 14 130 plate finite elements. Springs of suspension, forces in frictional wedges and in pivots are modeled with the help of built-in force elements. Forty modal coordinates were used for the description of flexible properties of the frame; total number of d.o.f. is 166.

For adequate representation of the real working conditions of the bay the following load blocks were considered:

- load (empty, one 40-foot container, two 40-foot containers, three 20-foor containers);
- railway irregularities (corresponding continuous welded rail and non-welded rail);
- macrogeometry (straight line, curves R=350 and 650 m);
- vehicle velocity.

Totally 168 various load blocks were considered. For each load block the correspondent numerical simulation was fulfilled. To automatize executions series of numerical experiments, the special *scanning* tool from the UM Optimization modules was used. This tool automates the fulfillment of series of numerical experiments, record course of experiments and save results of experiments on a hard disk for posterior analysis. Thus, the designer is released from monotonous execution of series of numerical experiments "manually" what saves working hours and removes errors, which people unfortunately incline to do. During the numerical experiments a great number of kinematical and dynamical performances of the mechanical system were saved for the posterior analysis.

Let us consider a computational aspect of the problem as well. It would take 5-6 days to fulfill all of 168 numerical experiments using one personal computer[2]. To accelerate numerical experiments a special UM tool – *service of distributed calculations* – was used. It runs parallel calculations using all computers which are reachable in a network and decreases time efforts correspondingly. It is a very effective tool for using in computer centers and laboratories. Using 4-6 computers from the local network of the Laboratory of Computational Mechanics simultaneously made calculations about 5 times as faster and finish all the numerical experiments during a day.

For each load block a file of modal coordinates was saved. Based on this file a special procedure within UM Durability calculates a stress tensor and then von Mises stresses were used as uniaxial ones. So time histories of von Mises stress in every node of the FE-mesh of the flexible body are input data for stress load analysis that precede the durability analysis.

Fig. 3 shows one of results of the stress load analysis - the distribution of maximal stress amplitudes for a quarter of the bay frame.
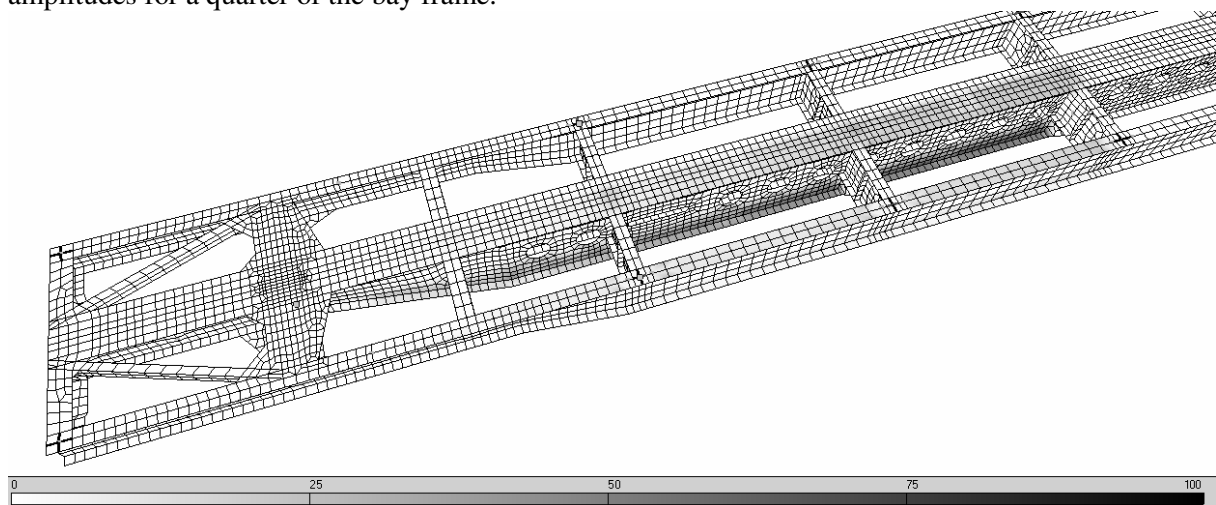

Fig. 3. Distribution of maximal stress amplitudes of the quarter of the bay, MPa
Рис. 3. Распределение максимальных амплитуд напряжений, четверть рамы, МПа

5.2. Durability analysis

Based on results of the stress load analysis and technological features more than 30 control areas were chosen for the subsequent durability analysis.

Characteristic parameters of the method are as follows.
- The durability evaluation is based on the linear damage accumulation Palmgren-Miner rule.
- S-N curve describes with a single line in double logarithmic scale.
- No mean stress correction.
- Description of the stress load as a combination of load blocks with corresponding relative part per nominal calendar period.

Relative parts of the load blocks were determined as follows. The relative part of run of the empty bay is 20% according to referenced data; other variants of load were taken as equally probable. For want of trustworthy data about relative parts of continuous welded rail and non-welded rail these parts were taken equal (50%). Relative parts of straight lines and curves of various radiuses as well as the distribution of vehicle velocity were taken according to statistical data for railroads in the Russian Federation.

Fatigue resistance properties were determined empirically based on their geometrical and technological features and recommendations from carriage engineering, see Table 1. Please note that

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[2] 2.4 GHz, 2 Gb RAM

the stress concentration factor is given by the interval. This will be reflected in results of the research below.

Fatigue resistance properties

Areas	Fatigue resistance factors					Total fatigue resistance reduction factor	Ultimate strength, MPa	Slope of S-N curve
	Material hetero-geneity	Streng-thening treat-ment	Scale	Surface condi-tion	Stress concentration factor			
Area A	1.1	1.0	0.85	0.85	2.5÷3.0	4.19	50.2	4.30
Area B	1.1	1.0	0.75	0.85	2.5÷3.0	4.75	44.3	3.79
Area C	1.1	1.0	0.85	0.85	2.8÷3.2	4.85	43.3	3.71
Area D	1.1	1.0	0.75	0.85	2.8÷3.0	4.75	44.3	3.79

Formula for life time predictions includes the value of an average daily run of the vehicle. This value has a significant dispersion from 200 up to 1100 km/day. Fig.4 shows the dependence of the life time prediction in years on a daily run of the vehicle (km/day). Curves 1, 2 and 3 correspond to maximal, average and minimal values of the stress concentration factor that gives us optimistic and pessimistic estimations. Line 4 shows minimal planned life time of the vehicle (32 years).

For each of the considered control areas the load blocks that lead to the most accumulated damage were selected. Relying on this data the most dangerous combinations of operation conditions from point of view of fatigue failure were obtained.
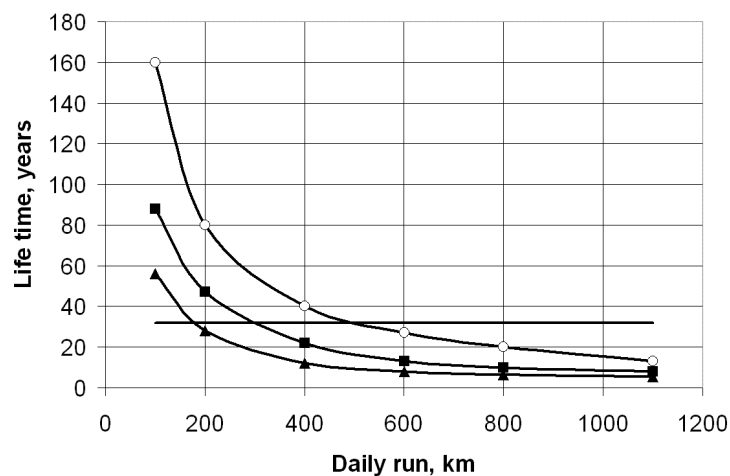

Fig. 4. Life time prediction vs. daily run
Рис. 4. Зависимость срока службы от суточного пробега

5.3. Experimental verification

Bench-tests of a full-scale bay frame were carried out by the test department of the scientific-promotional center "Carriages"[3]. Fig. 5 clearly shows that the crack that appeared during the bench-test starts at one of the dangerous areas and ends at the circle mesh in the middle of the frame where stress concentration factor is quite high.

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[3] Scientific-promotional center "Carriages", Russia, 190031, St.-Petersburg, Moscowskiy prospect, 9, see *http://nvc-vagon.ru/about/test_center.html* for details.

Thus from the point of view of a qualitative assessment there is a good convergence between results of the bench-test and durability analysis in UM software.

Quantitative results of the bench-test cannot be published in the present paper due to commercial reasons.

Bench-tests (top view)
Стенд для ресурсных испытаний (вид сверху)

Durability analysis in UM (bottom view)
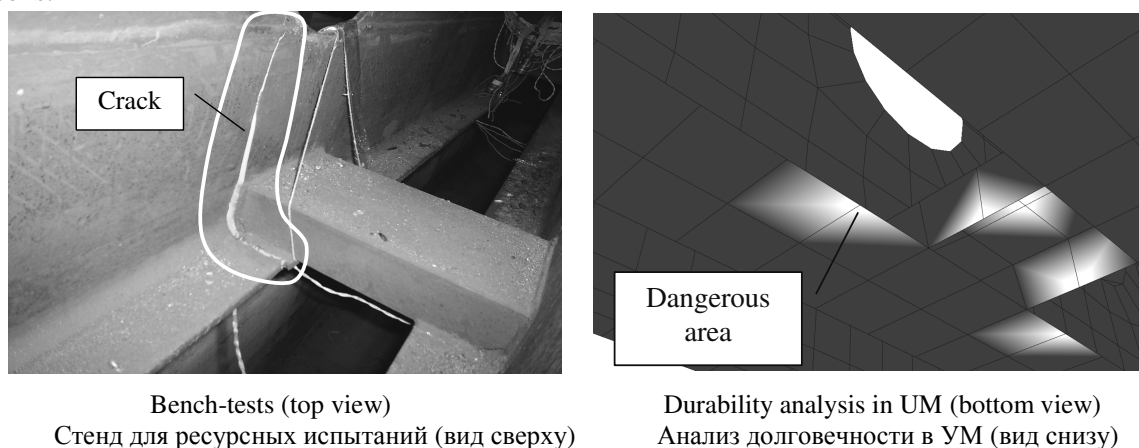Анализ долговечности в УМ (вид снизу)

Fig. 5. Comparison: the crack from the bench test and the dangerous area from durability analysis
Рис. 5. Сравнение: трещина в раме платформы после стендовых ресурсных испытаний и положение опас-
        ных точек после анализа долговечности

In consequence of lack of reliable data about working conditions and their relative parts as well as shortage of experimental data concerning material and fatigue resistance properties of elements of the frame with different geometry, machining and thermal treatment obtained results should be considered as mostly qualitative and cannot give us accurate quantitative prediction.

6. CONCLUSIONS

The extensively used now approach to durability analysis is usually based on results of several static calculations and take into account dynamic factor and the lowest natural frequency. Such an approach does not consider real stress-strain state in the parts during movement of the vehicle.

The approach, which is discussed in the present paper, gives the researcher a possibility for more accurate consideration dynamical properties and effects based on simulation of full 3D models of the vehicles under a wide range of their real working conditions during durability analysis.

The applied research considered in the sect. 4 shows good convergence between simulation and experimental results and proves that the presented approach can be successfully used for durability analysis in the context of complex analysis of dynamical and fatigue properties of railway vehicles.

7. ACKNOWLEDGEMENT

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