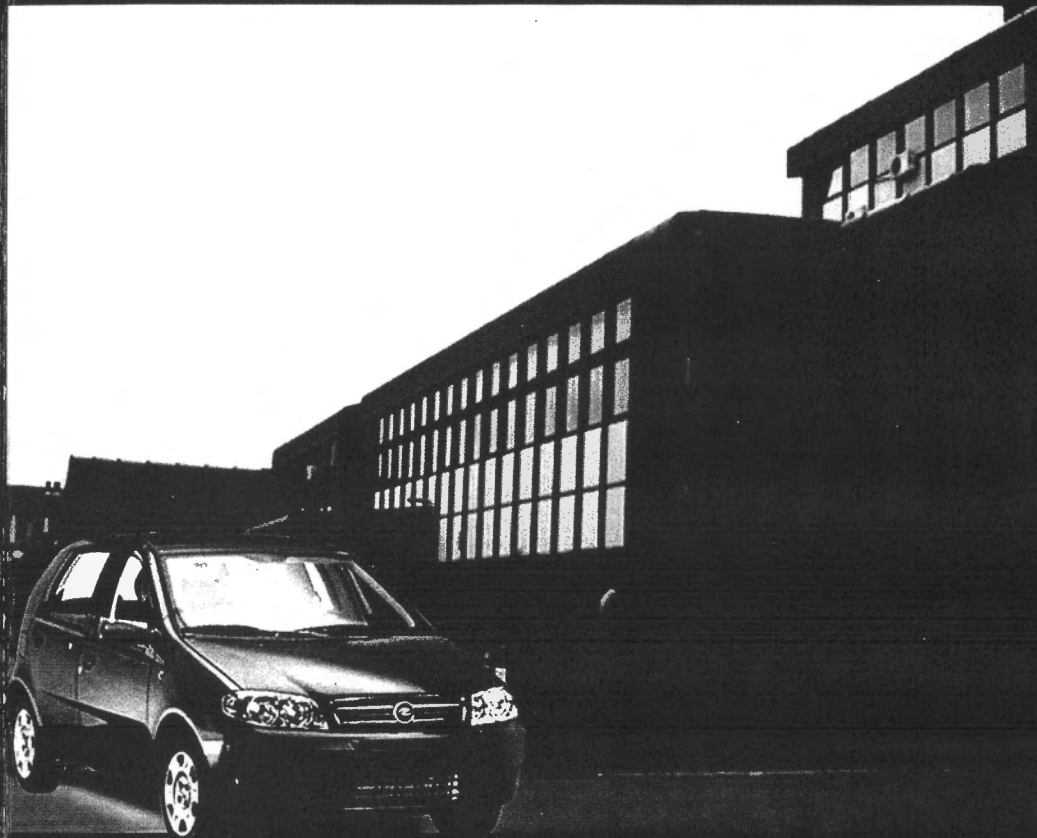

SUSTAINABLE DEVELOPMENT OF AUTOMOTIVE INDUSTRY

BOOK OF ABSTRACTS

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FOREWORD

Traditional organizing of international "MVM" Symposium became the brand Faculty of Mechanical Engineering and the University from Kragujevac. This year also, a considerable number of papers from the country and from abroad were omitted, as same as the traditional support from Ministry of Science, the city Kragujevac, our friends and contributors in manufacturing or servicing activities correlated to automobiles.

This time also, the papers from many scientists and researchers in the field of motor vehicles gave a specific impression to this meeting, though the presence of an increased number of papers from similar branches is also noticeable. Motor vehicles from their origin had a considerable attention both from the mechanical engineers and the business people, and in the process of vehicles development and implemented scientific achievements from various scientific fields. Motor vehicles have a wide user population, and they, with their own demands, impose new classes and new car categories. According to technical and technological trends in development, same as with different needs of the customers, a focus of car manufacturers is displaced towards to specific car types or car classes, but the car in general, as the actuality, a challenge and the need is still at the "stage".

It is quite clear that the car as the multidisciplinary object of progress and research from one side and as the object of need or prestige from the other one, is actually the target for development and investment. Besides, car is the means for connecting distant destinations more and more faster, and at the same time it has improved mobile performances within the city driving, and therefore as the object of traffic planning and traffic regulation take, without any doubt, the most significant place. Therefore there is the tendency of spreading of the participated papers outlines, namely, except of vehicles mechanics and the processes within the engine itself, a certain area is dedicated to fields such as management, recycling regulations, auto-electronic, economy, traffic.

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EXPLICIT DYNAMICS ANALYSIS IN WAGGON CRASH APPLICATION

ABSTRACT: This paper represents a set of knowledge and experience that the authors obtained through becoming acquainted with software package LS-DYNA, as well as with the kinds of problems that can be successfully be solved in this software. Due to developed algorithms for contact problem solving, LS-DYNA found a huge practice in the car industry, especially in the crash tests simulating. This paper contains analysis of the waggon-cistern crash into a still rigid barrier.

KEYWORDS: explicit dynamic, crash analysis, FEM

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INTRODUCTION

LS-DYNA is multipurpose software for explicit and implicit numerical integration of construction dynamic analyses and represents one of the most famous and best softwares that solves multiphysical problems.

The first part shortly presents the theoretical basis that the algorithms implemented in the software are based on. At the beginning, motion equations are presented and then the method of central differences is shortly described, so in the end we reach the modified method which is used in the software and the criteria to be fulfilled. In the very end of the theoretical part, there are basis of contact problems theory.

The second part of the paper processes the example of crash analyses, waggon-cistern crash into a rigid wall. The end of the paper is a general impression based on the up-to-date experience as well as some guidelines for the future work/tasks.

THEORETICAL BASIS

System motion equations

We observe a simple system with one degree of freedom, fig. 1, as well presenting the forces that influence the mass m .

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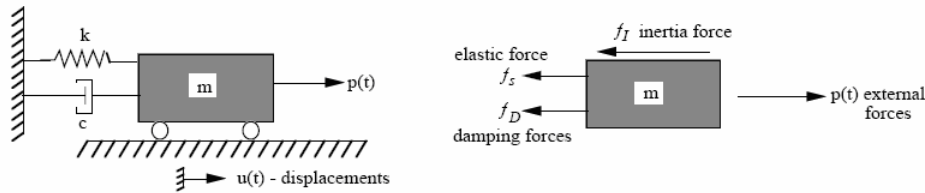


Figure 1 System with muffling with one degree of freedom; figure of system and forces that influence it

Equilibrium equation, derived from the use of d Alamber's principle is [1, 2, 3]:

$$f_I + f_D + f_S = p(t) \quad (1)$$

where the inertial force f_I , muffling f_D and rigidity force f_S are presented with the equations (2)

$$\begin{aligned} f_I &= m\ddot{u} & \ddot{u} &= \frac{d^2u}{dt^2} & \ddot{u} &- acceleration \\ f_D &= m\dot{u} & \dot{u} &= \frac{du}{dt} & \dot{u} &- velocity \\ f_S &= ku & u &- displacement & k &- stiffness \end{aligned} \quad (2)$$

Motion equation for linear problems is presented with equation (3), whereas the equation (4) is for nonlinear case:

$$m\ddot{u} + c\dot{u} + ku = p(t) \quad (3)$$

$$m\ddot{u} + c\dot{u} + f_S(u) = p(t) \quad (4)$$

Analytical solution is possible to determine only in linear differential motion equation. Dynamic response of unmuffled system under the influence of harmonious load is presented with equation:

$$u(t) = u_0 \cos(\omega t) + \frac{\dot{u}_0}{\omega} \sin(\omega t) + \frac{p_0}{k} \frac{1}{1 - \beta^2} (\sin(\bar{\omega} t) - \beta \sin(\omega t)) \quad (5)$$

where u_0, \dot{u}_0 is the initial displacement and initial velocity, $\frac{p_0}{k}$ is static displacement, $\frac{1}{1 - \beta^2}$ is a dynamic factor.

In this case, harmonious displacement is defined with the equation

$$p(t) = P_0 \sin(\bar{\omega} t) \quad (6)$$

In the equations above circular frequency $\omega = \sqrt{\frac{k}{m}}$ and load frequency $\beta = \frac{\bar{\omega}}{\omega}$ are figuring.

Integrations of differential motion equations

The only possible way to solve nonlinear problems is numerical. There are two methods of direct integration of differential motion equations. They are implicit and explicit methods of integration. The fundamental difference between these methods is the fact that in the algorithm of implicit integration the equation for time step t_{n+1} is being solved, while in the case of explicit method the equation for time step t_n is being solved. Besides that, implicit integration is unconditionally stable, regardless the size of the time step, whereas the explicit methods are conditionally stable, since it is necessary to choose a very small time step.

In LS-DYNA software the algorithms for numerical integration are developed that are based on explicit methods, or to say, on the central differences method. Practically, LS-DYNA uses the modified method of central differences.

Central differences

Discretization in method of central differences is presented on fig. 2.

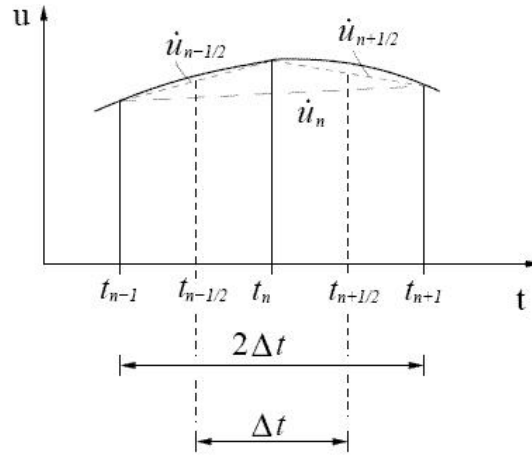


Figure 2 Discretization by central differences method

According to fig. 2, velocity and acceleration in the moment t_n are in the equations:

$$\begin{aligned}\dot{u}_n &= \frac{1}{2\Delta t}(u_{n+1} - u_{n-1}) \\ \ddot{u}_n &= \frac{1}{\Delta t}(\dot{u}_{n+\frac{1}{2}} - \dot{u}_{n-\frac{1}{2}}) \\ \ddot{u}_n &= \frac{1}{(\Delta t)^2}(u_{n+1} - 2u_n + u_{n-1})\end{aligned}\quad (7)$$

Equilibrium equation in the matrix form in the moment t_n is:

$$\mathbf{M}\ddot{\mathbf{u}}_n + \mathbf{C}\dot{\mathbf{u}}_n + \mathbf{K}\mathbf{u}_n = \mathbf{P}_n \quad (8)$$

where \mathbf{M} is mass matrix, \mathbf{C} is muffling matrix, \mathbf{K} is stiffness matrix, and \mathbf{P}_n is vector of outer forces. By replacing equation (7) in the equilibrium equation (8), we get:

$$\left(\mathbf{M} + \frac{1}{2}\Delta t\mathbf{C}\right)\mathbf{u}_{n+1} = \Delta t^2\mathbf{P}_n - (\Delta t^2\mathbf{K} - 2\mathbf{M})\mathbf{u}_n - \left(\mathbf{M} - \frac{1}{2}\Delta t\mathbf{C}\right)\mathbf{u}_{n-1} \quad (9)$$

In the moment $t = 0$, considering the initial conditions \mathbf{u}_0 and $\dot{\mathbf{u}}_0$, as well as $\ddot{\mathbf{u}}_0$, we get:

$$\mathbf{u}_{-1} = \mathbf{u}_0 - \Delta t\dot{\mathbf{u}}_0 + \frac{\Delta t^2}{2}\ddot{\mathbf{u}}_0 \quad (10)$$

As it was Iraedy said, method of central differences is conditionally stable, so the size of the time step is restricted.

Stability of central differences method

Stability of central differences method is defined by stability of the linear system. We are starting from coupled system of linear motion equations in modal equations.

$$\mathbf{u} = \phi_1x_1 + \phi_2x_2 + \dots + \phi_Nx_N = \Phi\mathbf{x} \quad (11)$$

Vector of eigen value, Φ , is normalized regarding the mass matrix and stiffness matrix:

$$\begin{aligned}\Phi^T \mathbf{M} \Phi &= \mathbf{I} \\ \Phi^T \mathbf{K} \Phi &= \omega^2\end{aligned}\quad (12)$$

With this normalization we get the equation for viscous muffling:

$$\Phi^T \mathbf{C} \Phi = 2\xi\omega \quad (13)$$

Motion equation for generalised displacements are:

$$\ddot{x} + 2\xi_i\omega_i\dot{x} + \omega^2x = Y_i \quad (14)$$

where

$$\Phi^T \mathbf{p} = \mathbf{Y} \quad (15)$$

Equations for generalised velocities and displacements towards central differences are:

$$\dot{x}_n = \frac{x_{n+1} - x_{n-1}}{2\Delta t} \quad \ddot{x}_n = \frac{x_{n+1} - 2x_n + x_{n-1}}{\Delta t^2} \quad (16)$$

By replacing the equation 16 in motion equation 14, we get

$$\begin{aligned}x_{n+1} &= \frac{2 - \omega^2\Delta t^2}{1 + \xi\omega\Delta t}x_n - \frac{1 - \xi\omega\Delta t}{1 + \xi\omega\Delta t}x_{n-1} + \frac{\Delta t^2}{1 + \xi\omega\Delta t}Y_n \\ x_n &= x_n\end{aligned}\quad (17)$$

Or to say, in the matrix form we have:

$$\begin{aligned}\begin{bmatrix} x_{n+1} \\ x_n \end{bmatrix} &= \begin{bmatrix} \frac{2 - \omega^2\Delta t^2}{1 + \xi\omega\Delta t} & -\frac{1 - \xi\omega\Delta t}{1 + \xi\omega\Delta t} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_n \\ x_{n-1} \end{bmatrix} + \begin{bmatrix} \frac{\Delta t^2}{1 + \xi\omega\Delta t} \\ 0 \end{bmatrix} Y_n \\ \hat{\mathbf{x}}_{n+1} &= \mathbf{A}\hat{\mathbf{x}}_n + \mathbf{L}Y_n\end{aligned}\quad (18)$$

where \mathbf{A} is the operator of the motion equation integration. After m time steps and $\mathbf{L} = 0$ we get:

$$\hat{\mathbf{x}}_m = \mathbf{A}^m \hat{\mathbf{x}}_0 \quad (19)$$

When $m \rightarrow \infty$, operator of the integration \mathbf{A} has to stay restricted. By special decomposition of operator decomposition \mathbf{A} we get:

$$\mathbf{A}^m = (\mathbf{P}^T \mathbf{J} \mathbf{P})^m = \mathbf{P}^T \mathbf{J}^m \mathbf{P} \quad (20)$$

where \mathbf{P} is orthonormed vector which contains eigen matrix \mathbf{A} , and \mathbf{J} is Jordan's form with eigen matrix values \mathbf{A} on the diagonal. Stability criterium is defined through radius of eigen values spectrum, $\rho(A)$, as:

$$|\rho(A)| \leq 1 \quad (21)$$

This way, criterium for \mathbf{J}^m to be restricted is fulfilled.

Eigen matrix values \mathbf{A} for unmuffled system are obtained from: za neprigušeni sistem dobijaju se iz:

$$\text{Det} \left(\begin{array}{cc|cc} 2 - \omega^2 \Delta t^2 & -1 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{array} - \lambda \begin{array}{cc|cc} 1 & 0 \\ 0 & 1 \end{array} \right) = 0 \quad (22)$$

where λ represents eigen matrix value \mathbf{A} . Solving the equation 2.2.14 for λ , and solving inequation:

$$\lambda \leq 1 \quad (23)$$

We get a critical value of the time pace, for a system without muffling,

$$\Delta t \leq \frac{2}{\omega_{\max}} \quad (24)$$

For system with muffling, critical time step is

$$\Delta t \leq \frac{2}{\omega_{\max}} \left(\sqrt{1 + \xi^2} - \xi \right) \quad (25)$$

By comparing the equations 24 and 25 it can be concluded that muffling reduces the size of critical time step. The following is valid for the variable size of time step:

$$\begin{aligned} \Delta t^2 &\leq \frac{4\delta_i}{\omega_i^2} \\ \delta_i &= \frac{\Delta t_i}{\Delta t_{i-1}} \\ 0 &\leq \delta_i \leq 1 \end{aligned} \quad (26)$$

Time integration is stable if the time step is being reduced. Time step is restricted by the biggest natural frequency of the system.

Time integration in LS-DYNA software

Discretization in LS-DYNA software is done for actual geometry, instead for the displacement. The principle of discretization is on the fig. 3.

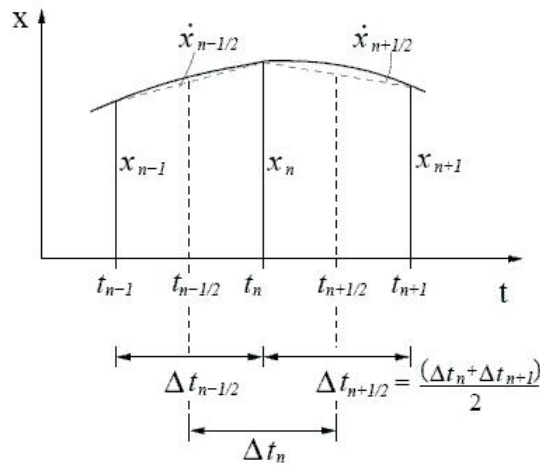


Figure 3 Discretization used in LS-DYNA software

Velocity is defined by the equation 27 and it is not a central difference, unlike the acceleration that represents the central difference 28.

$$\dot{x}_{n+1} = \frac{1}{\Delta t_{n+1}}(x_{n+1} - x_n) \quad (27)$$

$$\ddot{x}_n = \frac{1}{\Delta t_n}(\dot{x}_{n+\frac{1}{2}} - \dot{x}_{n-\frac{1}{2}}) \quad (28)$$

Motion equation for nonlinear case for the moment t_n is:

$$\mathbf{M}\ddot{\mathbf{x}}_n = \mathbf{P}_n - \mathbf{F}_n^{\text{int}} - \mathbf{C}\dot{\mathbf{x}}_n \quad (29)$$

where $\dot{\mathbf{x}}_n$ is unknown velocity in the moment t_n . As in central differences presented in the previous section, the matrix \mathbf{A} from the equation 2.2.12 . should be analysed here.

From the equation 29 we derive acceleration \ddot{x}_n , and from equations 28 and 27, $\dot{x}_{n+\frac{1}{2}}$ and x_{n+1} should be derived respectively. Considering the initial conditions in the equation 30., we get an equation 31 for the initial acceleration \ddot{x}_0 and velocity $\dot{x}_{\frac{1}{2}}$.

$$\begin{aligned} x_0 &= \bar{x}_0 + u_{stat} \\ v_0 &= \frac{1}{2}(\dot{x}_{-\frac{1}{2}} + \dot{x}_{\frac{1}{2}}) \end{aligned} \quad (30)$$

$$\begin{aligned} \ddot{x}_0 &= M^{-1}(P_0 + P_{stat} - F_0(u_{stat}) - Cv_0) \\ \dot{x}_{\frac{1}{2}} &= v_0 + \frac{1}{2}\Delta t_0\ddot{x}_0 \end{aligned} \quad (31)$$

In the equations 30 and 31 \bar{x}_0 is the original geometry, u_{stat} is the initial displacement from the static load.

There are no precisely defined stability conditions for integration in nonlinear problems. LS-DYNA uses standard method of central differences for boundary size approximation of the time step. Thus, LS-DYNA uses the size of the time step as:

$$\Delta t = 0.9\Delta t_{critical} \quad (32)$$

Here $\Delta t_{critical}$ is the time step determined according to the equation 26, or:

$$\begin{aligned} \Delta t_{crit}^2 &\leq \frac{4\delta_i}{\omega_i^2} \\ \delta_i &= \frac{\Delta t_i}{\Delta t_{i-1}} \\ 0 &\leq \delta_i \leq 1 \end{aligned} \quad (33)$$

For different types of elements time step is determined according to the equation form 34, where l is the element length, and c is the sound velocity. Equations for the specific types of elements can be found in [3]

$$\Delta t = \frac{l}{c} \quad (34)$$

CONTACT IN LS-DYNA SOFTWARE

As it was mentioned in the introduction, LS-DYNA is world-known software used for nonlinear dynamic problem solving. A big group of nonlinear problems represent as well contact problems. Contact analysis is the integral part of many problems in the field of big deformations. Precise modeling of the contact pair between the bodies is a key point considering the simulation possibilities using the finite element method.

There is a large number of contact types that are implemented or developed in LS-DYNA software. Certain types are developed and are used in specific problems, such as airbag contacts, edge contacts, and other, but also the types used in the general cases.

In LS-DYNA software, contact is defined by location identifying of slave segments that potentially penetrate into master segment. Identification is done through the parts, segments, sets of segments, sets of nodes, etc. Check of the penetration by using one of many algorithms is being done in each time step. In the case of penalty-based contact, when it comes to penetration, resistance force is given that is proportional to the penetration depth and finally eliminates the penetration. If it is not emphasized differently, we are talking here about penalty-based contact and besides it, there is the constrained-based contact as well. With this kind of contact a rigid body can be used, but it is recommended for the density of the rigid body not to be the same as of a deformable body, so that the force could be distributed realistically.

In crash analyses, deformations can be very big and the assumptions about where or how the contact will happen are difficult to make, sometimes even impossible. Thus, the automatic contact is recommended as a contact where the orientation is not defined, or to say, where the penetration can be detected at both sides of shell elements. Contact algorithm used in the case of automatic contact is better than the old type contact for working with separated nets.

AN EXAMPLE OF WAGGON CRASH TEST

This part presents an example of waggon-cistern crash into the still rigid wall. We are starting from a ready-made model, or in other words, from the finite element net that is made in FEMAP v9.0 software. Waggon crash is simulated with the 80km/h velocity, into still rigid wall. Waggon model is presented on figs. 4 and 5.

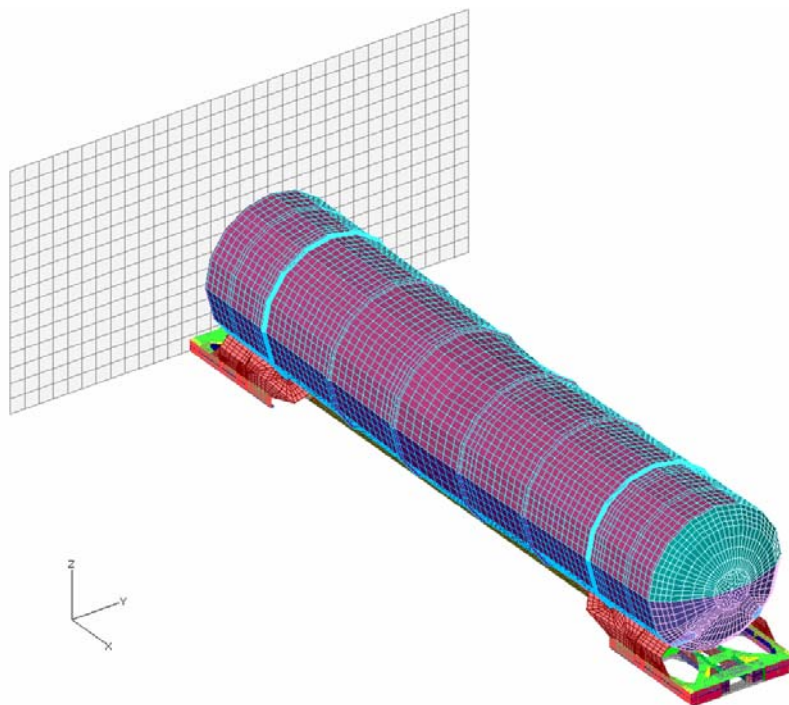


Figure 4 Waggon-cistern. Finite element mesh. Diametric view.

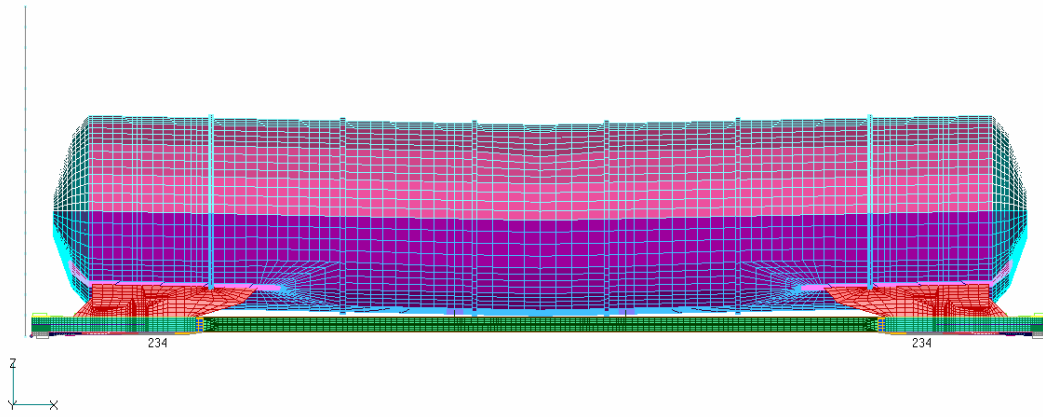


Figure 5 Waggon-cistern. Finite element mesh. ZX view

Waggon and the wall are modeled by elements of the shell. The whole model has 54324 elements, or 53578 nodes. Cistern model consists of 39 parts, or in other words, properties, which are defined by elements of different thickness shell, or by material that has the same ID as the property. The part determined by a property or material with ID= 40 is rigid wall model.

The analyses is done in LS-DYNA software, and then the achieved results are imported into FEMAP. Results of the analyses, or the field of effective stress in the last step of the analyses, are showed in figs. 6 – 8.

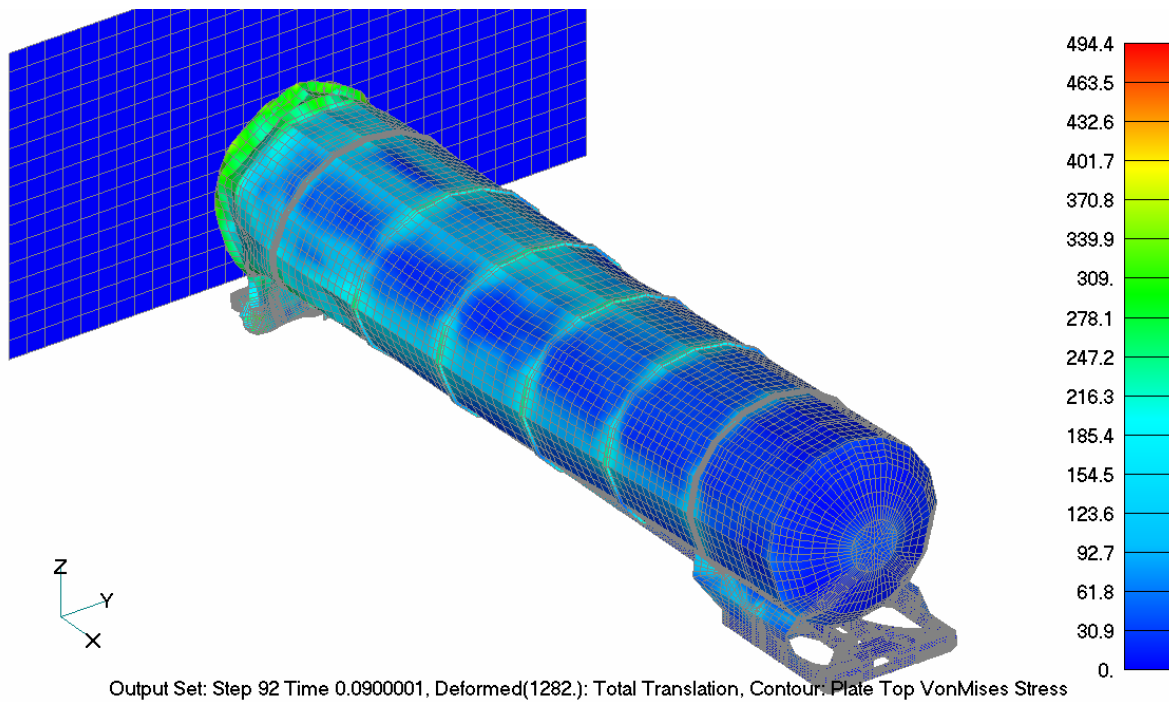


Figure 6 Crash test waggon-cistern; Effective Stress Field – Dimetric

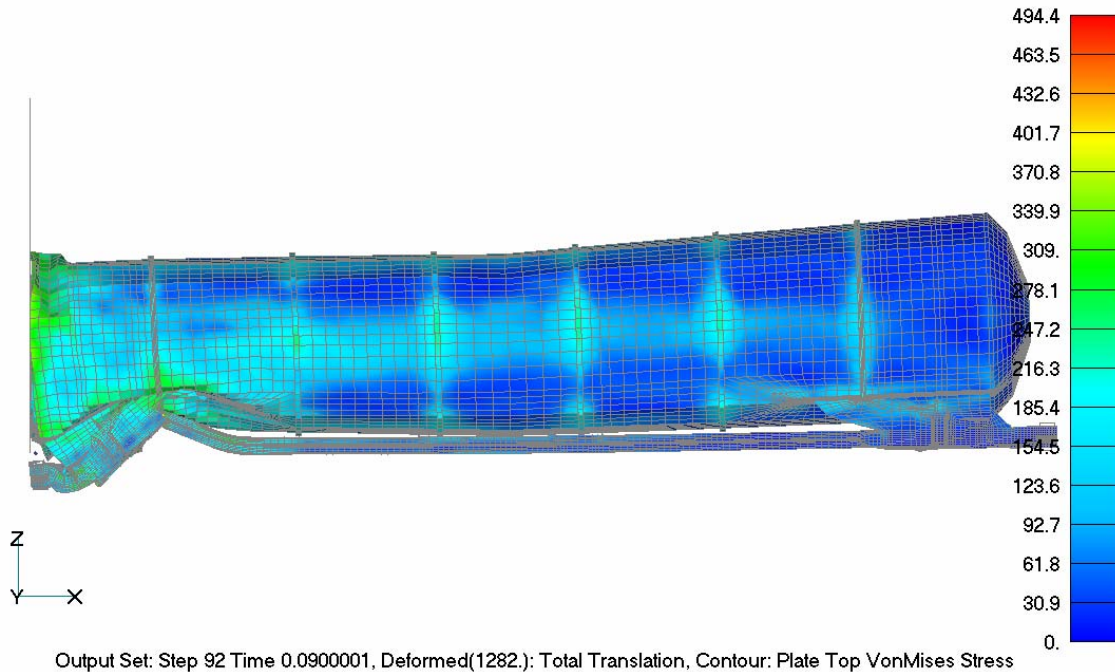


Figure 7 Crash test wagon-cistern; Effective Stress Field – ZX view

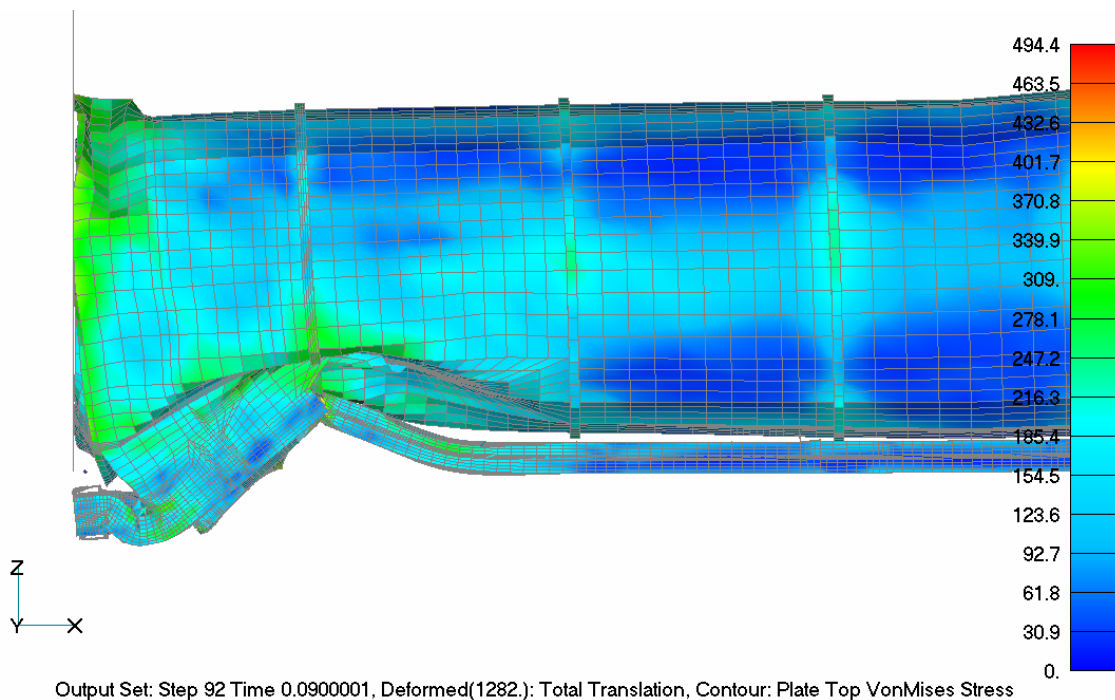


Figure 8 Crash test wagon-cistern; Effective Stress Field – ZX detail

CONCLUSIONS

The main goal of this paper was the synthesis of knowledge and data, that will help new users to become familiar with the functions and possibilities of LS-DYNA software, as one of the most developed and most frequently used in the world.

Within the theoretical basis the important facts are presented concerning solution stability as well as the mechanisms for determining the time step that will fulfill defined criteria. According to the analysed examples, the conclusion is that the time step is extremely small in solving problems by using explicit method of integration. For example, in the case of wagon-cistern crash into the still rigid barrier, time step was 10^{-7} seconds.

Further work on this topic would be expanding the field of use, primarily in the field of contact problems, but in the other fields of LS-DYNA software usage as well. In the field of contact problem solving, capacity of the software is

extraordinary, so the parameters should be well adjusted to obtain reliable results. Besides that, the software also supports solving of the multiphysical coupled problems, so that is the direction to follow.

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