Considerations on the Behavior of Vehicle Side Impact

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Abstract: - This paper is intended to introducing in the large study conducted by the authors regarding overall side impact and influence of deformations on the victims in particular. A series of test structures has been created, for the realization of a technical system that interfere with an IT system of measurement. In this purpose a methodological system has been set for the design and realization of the simulated test procedure platform and measurement chain. Vehicle side structure and occupant behavior determined at this stage are: occurrence of deformation mechanism and injuries that are representative of different applications and actual road events investigations practices which take into account of speed.

Key-Words: road events, eccentric side impact, crush energy, injury, experimental tests, investigation procedure

1 Introduction
Every year road side impact events produce victims whose mortality is 25% of the total. These type of collisions exerted extremely violent forces and accelerations on the occupants car because the space between the victim and vehicle components (non-lethal space) is limited. Serious injury result from the side impact collisions because the side structure is less rigid than the front part.

Modelling and simulation of traffic events require laborious technical procedures. In practice, engineers and experts investigators, estimate the severity of road event and initial condition movement using data such as braking distance, the coefficient of adherence and energy consumption. Sometimes braking tracks are not preserved and collected, or the vehicle is moving on surfaces (wet, snowy or high traffic areas) which do not retain traces of tire [2].

A lot of models have been developed that allow investigators to match the damage geometry with the energy consumed in collision. Some of these analytical models emphasize the link between crush and vehicle speed before the collision. All these models primary target is the victims and the vehicle behavior simulation during the event, and the accuracy is validated by comparing simulation data of interest from the experimental tests obtained from tests in laboratory or field conditions [1].

Many programs were conducted to help the engineers to accurately estimate vehicle speeds and their behavior before the collision. This research is conducted using a program called Virtual Crash22, which is used by most engineers and expert investigators for reconstruction of road events and provides information that leads investigators to a better understanding of side impact application tasks and how they are transformed into deformation energy of the vehicle structure. This paperwork provides valuable reference material for the investigators to reconstitute road events [3].

Crash tests from the front, side and rear, were performed. Crush energy determined by using data from experimental tests provide researchers a better understanding in terms of stiffness variation of the vehicle side [5]. The techniques used, data collected and the obtained results from the experimental tests are presented in this paper with the conclusions and recommendations for the future. Methodical investigation of collisions include measuring and comparing data collected, from the site of the road event with the data obtained from experimental tests [4]. This study contributes to the evaluation and comparison of lateral stiffness of the vehicle structure at various points. As the criterion for comparing the results of different tests is the size of deformation energy absorbed by the vehicle elements.

2 Side impact energy
In the side impact collision the driver and occupants are subjected to high solicitation loads in comparison with other types of collision with the same level of crush energy absorbed [7].

The procedures for investigating road events suppose that the determined strain energy with the measured deformations of the vehicle to contribute in determining the vehicle speed at that moment. So the amount of
deformation energy for two vehicles can be checked by providing energy losses with the help of dynamic timing analysis (PC-, Virtual-Crash). Using hand calculation methods we can obtain reasonable estimations, instead they are extensive, laborious and requires deep knowledge in the field [6]. The kinetic energy of a colliding vehicle with a massive and rigid structure (pole, tree, and bridgehead) has the following form:

\[ E_c = 0.5 \cdot mV_i^2 = 0.5 \cdot \frac{G}{g} V_i^2 \]  

(1)

where \( m \) is mass, \( G \) - weight of the vehicle in motion, \( g \) - acceleration of gravity and \( V_i \) - initial speed of the vehicle. The analysis will consider true the assumption according to which before the impact the car has only translational kinetic energy, and at the moments of the collision, the law of conservation impulse is applied respectively the kinetic moment.

Part of the vehicle's kinetic energy before the collision is converted to strain energy and another part in energy consumed thru the movement of translation and/or rotation. From energy considerations based on energy conservation law the energy balance will be established:

\[ E_t = E_{def} + E_{dc} + E_r \]  

(2)

where

\( E_t \) is total energy

\[ E_t = 0.5 \cdot mV_i^2 \]  

(3)

\( E_{def} \) is crush energy

\[ E_{dc} = 0.5 \cdot mV_f^2 \]  

(4)

\( E_r \) - rotational kinetic energy

\[ E_r = 0.5 \cdot I\Omega_f^2 \]  

(5)

During vehicle collision, they suffer both elastic and plastic deformations. Structural behavior of the vehicle during the collision can be modeled in different ways. An energy measurement uses the concept of compensation to identify the elastic properties of the collision by defining rejection speed (recoil) as a percentage of the vehicles speed before impact.

This method is presented below. The behavior of the side of a vehicle during the collision is generally defined as a function of the deformation form [7]. The simplest mathematical model considers the deformation forces as constant throughout the collision, \( C_i \). Under these circumstances the medium force during impact is \( F_i = \text{constant} \) where \( i \) represent the number of collisions with impact in the same place, and the average constant force is calculated using the total energy of the collisions structure, the strain energy is given by:

\[ E_{def} = F_i \cdot C_i \]  

(6)

\[ E_{def} = \sum_i E_{def} \]  

(7)

Presentation of the simplified model of deformation is expressed as a linear function of the impact \( F = kx \), is:

\[ E_{def} = \int Fdx = 0.5 \cdot kc^2 \]  

(8)

These conditions are applicable at the stage preceding the appearance of the deformation in ideal conditions of transmission of force.

To correlate the impact with a fixed vertical cylindrical obstacle (pole), in this study, simple linear models were used.

3 Coefficient of restitution

The mechanism of the collision can be represented with a high degree of accuracy realized in speed-time coordinates, where the initial moment will be considered when the collision is initiating. In the moments before impact initiation it is considered that the velocity (\( V_i \)) is stabilized at the desired clash value at least one second before. Starting with the \( t_0 \) origin of time the vehicle changes its velocity (\( AV \)), the obtained characteristic presents the general function of speed-time, being useful to study the vehicle behavior at impact. Its allure presents the shape of a simple harmonic oscillations with a period of 0.075 s, has the form:

\[ m \left( \frac{d^2 x}{dt^2} \right) + kx = 0 \]  

(9)

During centric collisions the speed varies continuously, permanently changing its sense and direction (velocity becomes negative) period during which the vehicle changes its geometric configuration by deforming. After measuring deceleration, we can express
the vehicle displacement. Because the impact is not centric but it's eccentric we can analyze recorded impulse on transverse direction (axis - y), but also yaw moments. By integrating vehicle deceleration, we get a graphic that presents the relationship between acceleration, speed and deformation, Figure 1.

![Dynamic behavior of the vehicle](image)

**Fig. 1 Dynamic behavior of the vehicle**

where

- curve 1 is speed
- curve 2 - the variation of the center of mass speed for a *non-centric* impact with an vertical cylindrical obstacle.
- curve 3 - acceleration
- curve 4 - displacement

When the collision speed (post crash) is zero, one can make the claim that the deformation is maximum. The relative velocity in the rebound phase increases negative to the final separation velocity, during which the vehicle bounce out of obstacle. Length of contact between the two masses include times during deformation and restitution phases. When the relative acceleration is zero and the relative speed of separation achieve maximum recoverable value we have separation of the two masses. Experimental test data of the collision are presented in spreadsheet mode, Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_i$ (m/s)</td>
<td>11.1</td>
</tr>
<tr>
<td>$V_r$ (m/s)</td>
<td>2.2</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>0.2</td>
</tr>
<tr>
<td>$D_d$ (m)</td>
<td>0.53</td>
</tr>
<tr>
<td>$D_r$ (m)</td>
<td>0.5</td>
</tr>
<tr>
<td>$t_2$ (ms)</td>
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</tr>
<tr>
<td>$E_t$ (kJ)</td>
<td>42.4</td>
</tr>
<tr>
<td>$E_{dc}$ (kJ)</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Restitution ($\varepsilon$) is defined as the ratio of the speed of rejection ($V_r$) and initial speed ($V_i$) as follows:

$$\varepsilon = \frac{V_r}{V_i} = \frac{P_r}{P_C} = \frac{v_2 - v_1}{v_{01} - v_{02}}$$  \hspace{1cm} (10)

The coefficient of restitution is the ratio of the relative velocity of the centers of mass of the vehicle at the end of the collision phase and their relative speed at the beginning of the collision phase. The velocities at the end of the impact being known, one can determine the kinetic energy consumed during the collision as the shape of deformation energy:

$$E_{def} = \frac{m_1 \cdot m_2}{2 \cdot (m_1 + m_2)} \cdot (1 - \varepsilon^2) \cdot (v_{01} - v_{02})^2$$  \hspace{1cm} (11)

For $\varepsilon = 0$, the maximum value of $\Delta E$ is specific to elastic collisions, while for $\varepsilon = 1$, the energy consumed during the collision is zero ($\Delta E = 0$, elastic collision).

From a technical point of view the restitution for centric collisions is defined although the concept can be used in non-central collisions with small derivations. The application of restitution in off-center collisions must be made with caution, because applying the concept becomes very complex when the gyration effects are involved. Note that the refund in case of vehicle collision is usually quite low, being between 5-15%, so its effect on the total kinetic energy is often ignored in the calculations of the road event reconstruction.

The speed of rejection ($V_r$) can be determined by analyzing the optical information offered by high-speed video camera 1500 fps on center mass position change within an interval of 1500 successive frames. Using rotation post impact factor used in most experimental tests, the center of mass of the vehicle does not always move in the opposite direction of the initial velocity ($V_i$), as expected in case of the impact in the central area:

$$\varepsilon = \frac{V_r}{V_i} \approx \frac{x_r}{x_i}$$  \hspace{1cm} (12)

where

- $V_r$ - rejection speed
- $V_i$ - initial speed
- $x_i$ - mass center position before initiating collision
- $x_r$ - successive positions of the center of mass in the range of 1500 fps from the start collision.

This technique proved to be superior to the measurement of variation in time of the equivalent distance. Taking in consideration the positioning of the camera objective and the markers from the fare side plain we can retain the parallax error can be out of it for all areas covered by working angle lens. In this context the distance between the center of the maximum deformation and the bumped obstacle it will be measured continuously and at the end a sketch of shadows will be created from the surface of the road and the state of the obstacle in case of the wood trunk.
4 Yaw movement

During lateral collision with a vertical cylindrical obstacle of unique radius, the central forces induce to the vehicle a particular rotating angular velocity. This induced angular velocity ($\omega$) will continue to grow, with the deformation of the vehicle body elements, until it reaches the maximum level. For calculating the energy absorbed by deformation of the vehicle structure resulting rotational energy must be subtracted from the total energy of the impact. The rotation induced as a result of vehicle impact is composed of:

- rotating phase of the vehicle around the obstacle collided;
- rotation phase of the vehicle after separation from the obstacle collided. At this stage, the rotational speed decreases thanks to interaction between tire and road surface area. In general, the angular velocity reaches the maximum value at the end of the collision phase.

The moment of inertia during the rotation of the vehicle take into account the two components of inertia:

\[ I_0 = m \cdot k^2 \]  
\[ I_p = m\left(k_{m}^2 + \xi^2\right) = \frac{G}{g}\left[k_{m}^2 + \xi^2\right] \]

where $m$ is mass of the vehicle, $G$ - vehicle weight, $k$ - radius of gyration, $\xi$ - distance from the point of impact to the center of mass ($C_g$), $I_0$ - moment of gyration and $I_p$ - moment of inertia of vehicle that rotates around the point of impact, Figure 2.

Rotation, after separation, is supposed to be around the center of mass ($C_g$), since contact with vertical cylindrical obstacle is to the final position.

Energy angular velocity is calculated using the inertia moment $I_0$ from the center of mass of the vehicle. Center of mass was determined by weighing the individual vehicle measurements without load. Were not taken into account changes in the position of the center of mass or $I_0$ yaw moment during the collision. When collision occurs in a direction perpendicular to the side of the vehicle and passing through the center of mass, distance from the point of impact at the center of mass is quite common who connecting the mass center with side of the vehicle, Figure 2 c. Since the angular velocity is small, rotational energy of the collision can be neglected.

So, to determine the vehicle deformation energy consumption, it reduces the rotational energy of the kinetic energy of translation resulting in the equation:

\[ E_{def} = (E_r - E_{dc}) - E_{rot} \]

Velocity of mass center does not vanish, but change its position by gyration movement.

4.1 Calculation of deformation energy

4.1.1 Methods and models of deformation

In the main, the principal objective of the research road events consists in determining the speed vehicles in the collision phases pre-crash, crash and post-crash. As basic approaches to reconstruction of road events are used: pulse method, based on the laws of conservation of linear momentum and angular and deformation method based on the laws of conservation of linear momentum, angular momentum and energy.

Using deformation method requires the existence or adoption of deformation models expressing the correlation between collision normal force per unit deformed area width and amplitude deformations. Deformation models can be static or dynamic.

4.1.2 Static model based on linear force-deformation characteristic

The linear dependence of force and amplitude of residual deformations was the basis for the first studies to determine the stiffness coefficients, the results being obtained from vehicle impact tests with fixed rigid barrier. The most common method for determining the
strain energy, used to investigate collisions, is introduced by Campbell, based on vehicle collision with fixed rigid barrier.

The linear dependence of impact velocity and deformation is given by:

\[ V_i = b_1 + b_0 \cdot \Delta_D \] (16)

where: \( V_i \) – initial speed; \( \Delta_D \) - remanent deformation;
\( b_0 \) - maximum speed at which residual deformations not occur; \( b_1 \) - the ratio of the impact speed and the average amplitude of deformations.

Figure 3 presents the ideal deformation - force characteristic. She expresses the dependence of the force per unit width of the deformed area and the average amplitude of dynamic deformation.

\[ F = A + B \cdot \Delta_D \] (17)

where \( A \) – stiffness coefficient representing the maximum force per unit width of the surface, where there are no residual deformations [N/m]; \( B \) – stiffness coefficient which is the ratio of the maximum force per unit width of contact area and the average amplitude of the deformation [N/m2]; \( \Delta_r \) – residual deformation; \( \Delta_D \) – dynamic deformation

The energy consumed in the collision can be expressed by the relation:

\[ \int_{0}^{L} \left( A \cdot \Delta_D \cdot \frac{B \cdot \Delta_D^2}{2} + G \right) dl \] (18)

where \( L \) - deformed profile width [m]; \( G \) - the integration constant representing the mechanical work done in the field of elastic deformation [N];

5 Experimental analysis and electronics
Subject vehicles undertaken to experimental side impact testing were foreseen with acceleration measurement devices, Figure 4, and yaw sensors, Figure 5, in the center of the mass or as close as possible to it applying after correction formula for the measured data, Figure 4.

The sensors were applied on the opposite side to the impact, directly on the structure elements of the body and in case of front axle measurement the sensor was positioned in the area of the inner wing [9].

Fig. 3 Deformation-force linear characteristic

Fig. 4 Accelerometers sensors

Fig. 5 Yaw sensor

In the same way the measurement sensors are mounted on the A and B poles but mirror on the opposed A and B poles.

6 Conclusions
The results of this study allow generalization of the characteristics of energy dissipation in the lateral side of the vehicle.

During collision of a fixed vertical cylindrical obstacles the energy turns in strain energy of the side of the vehicle, and the information regarding the
deformation can be used in reconstructing road events. Only data obtained from tests vehicle collisions are compared with similar technical characteristics.

The paper presented a test procedure where is performed a reversibly collision, namely the obstacle collides the vehicle which otherwise is in rest. Although this working mode is not always met in practice, the test procedure may be considered valid to study the energy absorbed during road event.

Modern vehicles must meet consumer requirements regarding performance and safety features. One should remember that the results of experimental tests could be erroneously interpreted and conclusion could be erroneously placed that the lateral limits of the cabin are not capable to provide non-lethal space to the passengers.

Test procedures used in the present are expensive and requires time in relation to the proposed solution.

The proposed solutions come to support road events research and implicitly determine the causes of their occurrence.

In the future this experimental test procedure is intended to be extended to the rear side behavior and rollover during road events research.

References: