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Experimental and analytic determining of the characteristics of deformation and side stiffness of a motor car body based on results of side-impact crash tests

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Abstract. Front-to-side collisions of motor vehicles very often occur on Polish roads. Every fourth road accident may be defined as a collision of this kind between moving vehicles. The analysis of accident effects, including the accident reconstruction process, is usually based on results of measurements of post-accident vehicle deformation and on information about vehicle body stiffness. Unfortunately, the information about the characteristic curves that would represent the deformation of a car body side is hardly available.

The objective of this study is to present a method of determining the characteristics of deformation and side stiffness of a motor car body based on crash test results. This objective was pursued with using results of NHTSA crash tests and of crash tests carried out at PIMOT. The analysis covered herein has been based on crash tests representing front-to-side collisions of motor cars, motorcycle impact against a car side, and frontal impact of a car against a barrier. Based on a combined analysis of the course of such experiments, mathematical models have been built that describe the dynamics of the deformation process in the vehicle contact zone. The model calculation results obtained with using results of measurements carried out during the crash tests have been worked out with using the linear regression method.

Based on the experimental and analytic methods, curves were plotted that represented the impact force as a function of the deformation of individual car bodies and then the characteristics of car body side deformation were determined. The range of this deformation and the hazard arising from the side impact to vehicle occupants were also shown. A special aspect of this hazard has also been unveiled by the calculation results, according to which the side stiffness of a car body decreases with growing deformation depth. In the initial deformation phase, this stiffness is even by 35 % higher in comparison with that observed when the vehicle body side is deformed by more than 20 cm.

1. Introduction

Front-to-side collisions of motor vehicles and motorcycle impacts against a motor vehicle side constitute a serious road traffic safety problem, as the fatalities in such accidents made in 2017 almost

20 % of all the killed in road accidents in Poland [6]. Every collision of motor vehicles is connected with a deformation of vehicle bodies. The post-accident vehicle body deformation is to some extent a source of information about the course and nature of the collision. The knowledge of the deformation size is often a crucial link in the road accident reconstruction processes. Extensive reviews of accident analysis and reconstruction problems together with descriptions and examples of the applications of empirical and analytical methods may be found, *inter alia*, in [5, 7, 9]. In publications [1, 3, 4, 12, 14, 15], work results have been presented where e.g. the collision energy and pre-impact vehicle velocities were determined from the deformation of vehicle bodies. Publications dealing with the characteristics of deformation and stiffness of the front part of motor vehicle bodies are quite easily available (e.g. [2, 8, 11]), but there is a distinct lack of information of this kind about the properties of the side part of motor vehicle bodies.

The notions of stiffness and deformation are closely connected with each other. Based on the history of a force and the resulting deformation, the deformation vs force curve and the value of stiffness of a vehicle body may be determined. Tests and analyses of front-to-side vehicle collisions, aimed at exploring this issue from this point of view, were carried out e.g. in [5, 7].

There is a lack of data characterizing the properties of a vehicle body side that are necessary for the analysis and reconstruction of road accidents. Therefore, a need has arisen to collect and systematize information about both the side stiffness of a vehicle body and the characteristics of the body side deformation caused by a road accident.

In this work, a convenient method was sought to determine the deformation and the value of stiffness of a vehicle body side. With this objective in view, results of experiments carried out by the National Highway Traffic Safety Administration (NHTSA) in the USA and by the Automotive Industry Institute (PIMOT) in Poland were used. These results provided a basis for analytical computations where histories of the forces deforming the front of the impacting vehicle (vehicle A) and the side of the impacted vehicle (vehicle B) were determined. In the next step, force vs deformation curves were determined for the combined deformation of both vehicles in their contact zone, which were afterwards taken as a basis for estimating the stiffness of the impacted vehicle's body side. In the PIMOT experiments, a motorcycle was used as the impacting vehicle.

2. Experimental tests

The objective of this work was pursued with using results of front-to-side crash tests carried out at NHTSA according to the special Federal Motor Vehicle Safety Standard (FMVSS) 214 procedure [10, 13], where motor vehicles of various makes and models frontally struck a side of the body of a Honda Accord car (year of manufacture 2004, gross vehicle mass 1640 kg). The kinematics of motion of the vehicles involved during such a test has been described in [10]. The contours of the average deformations of vehicles A and B and data of the impacting vehicles have been outlined in Fig. 1.

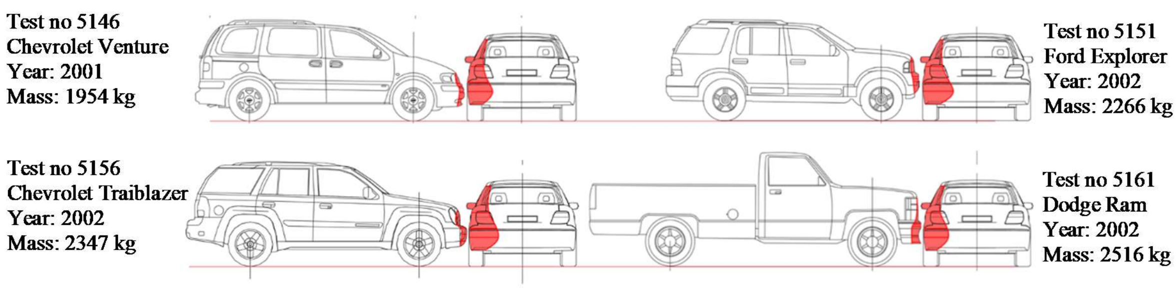

Figure 1. Zones of deformation of vehicles A and B in the front-to-side crash tests [16-19]

The study was started from an analysis of the characteristics of deformation of the front body parts of the impacting vehicles. The computed impact force vs vehicle body deformation curves have been presented in Fig. 2.

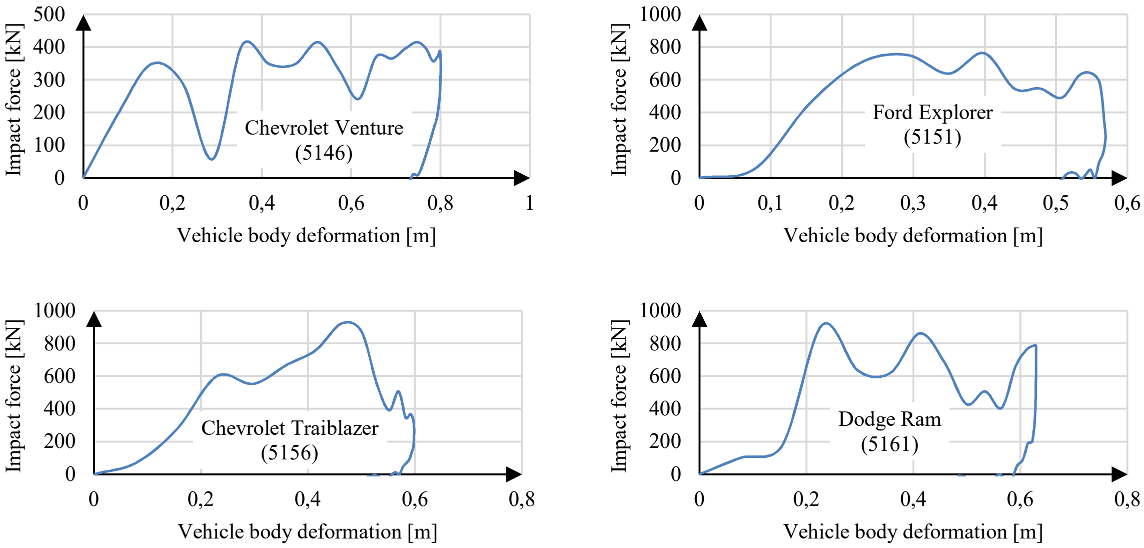

Figure 2. Characteristics of deformation of the front body parts of the impacting vehicles [16-19]

Additionally, results of two crash tests with a motorcycle hitting a motor car side, carried out at the Automotive Industry Institute (PIMOT) in Warsaw, were used. In the tests, a motorcycle moving with a speed of 50 km/h struck the left pillar B (experiment 1) and left front door (experiment 2) of a motionless motor car. The results of these experiments enabled determining the characteristics of deformation of a motor car body side (Fig. 3).

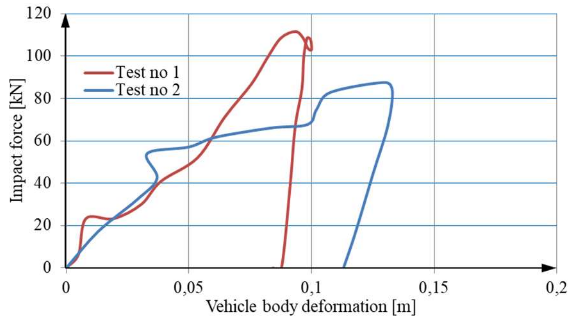

Figure 3. Characteristics of deformation of a motor car body side struck by a motorcycle

3. Analytical computations

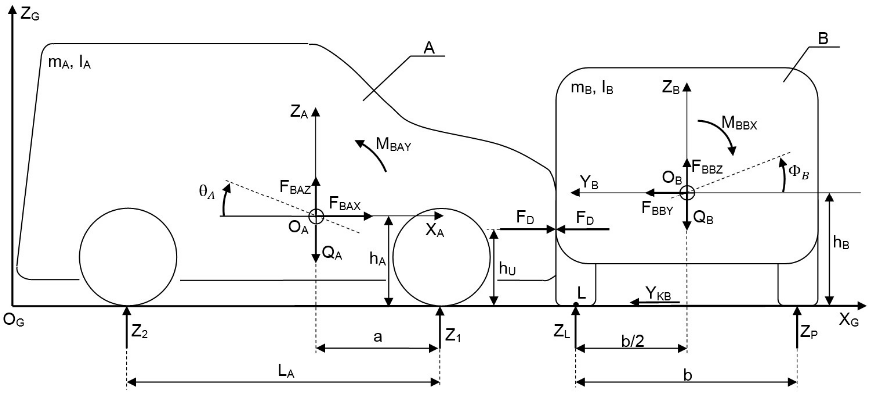

Figure 4. System of forces during a front-to side vehicle collision, assumed for the computations.

Fig. 4 shows the system of forces that act on vehicles involved in a front-to-side collision, built on the grounds of the collision models presented in [9]. Based on this, the following equations of equilibrium of the forces acting on vehicle B were formulated:

$$\sum(X_G)_B = 0 \rightarrow F_D - F_{BBY} - Y_{KB} = 0 \rightarrow F_D - m_B\ddot{y}_B - \mu(Z_P + Z_L) = 0 \tag{1}$$
$$\sum(Z_G)_B = 0 \rightarrow Z_L + Z_P - Q_B - F_{BBZ} = 0 \rightarrow Z_L + Z_P - m_B g - m_B\ddot{z}_B = 0 \tag{2}$$
$$\sum(M_L)_B = 0 \rightarrow Z_P b + F_{BBY}h_B - M_{BBX} - F_D h_U - Q_B\frac{b}{2} + F_{BBZ}\frac{b}{2} = 0 \rightarrow$$
$$\rightarrow Z_P b + m_B\ddot{y}_B h_B - I_B\ddot{\Phi}_B - F_D h_U - m_B g\frac{b}{2} + m_B\ddot{z}_B\frac{b}{2} = 0 \tag{3}$$

In the equations, the following notation was used (subscript B indicates vehicle B):
$\ddot{z}_B$, $\ddot{y}_B$ – components of the vector of acceleration of the vehicle mass centre in the global coordinate system $O_G X_G Z_G$;
$\ddot{\Phi}_B$ – component of the vector of angular acceleration of the vehicle body;
Z_L, Z_P – normal road reactions acting on the left and right wheels of vehicle B, respectively;
m_B, I_B – vehicle mass and moment of inertia, respectively;
b – wheel track of vehicle B;
h_B – height of the centre of vehicle mass;
h_U – height of the centre of the area of contact between the vehicles during the collision;
μ – tyre-road adhesion coefficient;
F_D – vehicle impact force.

Equations (1)-(3) were used for determining the vehicle impact force F_D and then the force vs deformation curves for the bodies of vehicles A and B. In this work, a method of determining the vehicle body stiffness value was chosen that was based on the deformation characteristic curve. To calculate this curve, an assumption was made that the difference between the displacements of vehicles A and B (along the longitudinal axis of vehicle A) represents the combined (averaged) deformation of the vehicle bodies. Therefore, the following equations might be written:

$$F_D(t) = F_{BXA}(t) = m_A * \ddot{x}_A(t) \quad (4)$$
$$C_D(t) = x_A(t) - y_B(t) \quad (5)$$

where:
$C_D(t)$ represents the combined (summed-up) deformation of both vehicles.

Displacements $x_A(t)$, $y_B(t)$ were calculated by numerical integration of components of the vectors of acceleration of the centres of vehicle mass along axes O_AX_A and O_BY_B of the local coordinate systems. Based on the computations, force vs deformation curves characterizing the combined deformation of bodies of vehicles A and B were plotted, which have been presented in Fig. 5. Further computations were carried out with using the parts of the said curves that represented a growth in the impact force because they were taken as a basis to estimate the vehicle body stiffness values.

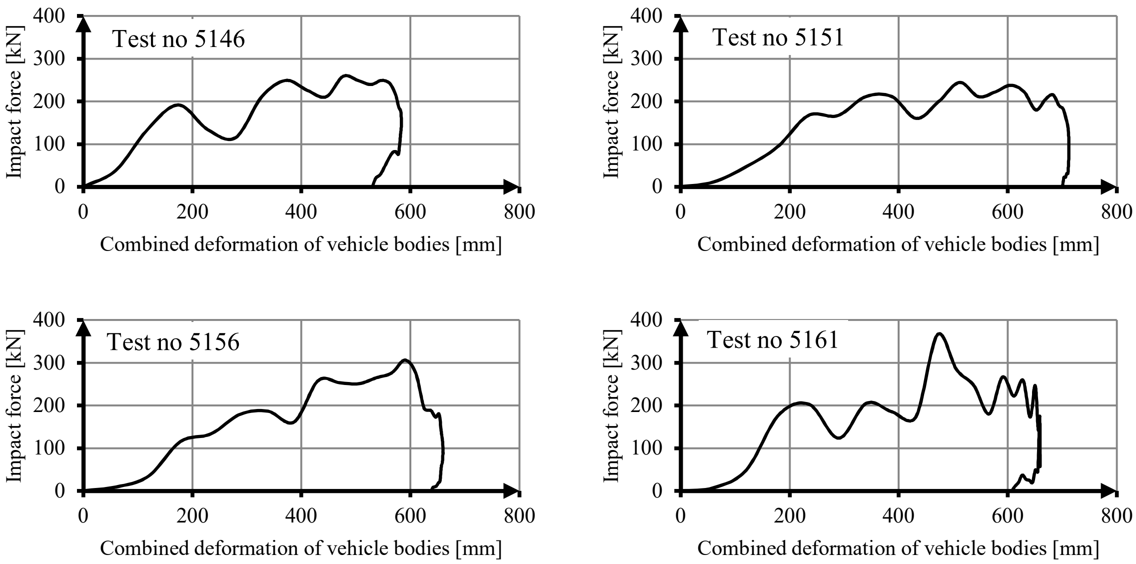

Figure 5. Characteristic curves for the combined deformation of bodies of vehicles A and B [16-19]

Since both vehicle bodies are deformed by the same force, the averaged (segmental) stiffness values can be determined. This may be done for elementary increments of force ΔF_D and deformation ΔC during the impact. Such an assumption makes it possible to divide the characteristics of combined deformation of bodies of vehicles A and B (Fig. 5) into the separate characteristics of deformation of individual vehicles.

The following equations were assumed to hold:

$$\Delta F_D = k_A \Delta C_A \text{ and } \Delta F_D = k_B \Delta C_B \quad (6)$$

where:
$\Delta F_D = F_D(t + \Delta t) - F_D(t)$ is a change in the deformation force during a time increment Δt, adopted as 4 ms in these computations;
$\Delta C_{A/B} = C_{A/B}(t + \Delta t) - C_{A/B}(t)$ is the corresponding change in the deformation of bodies of vehicles A and B;
k_A, k_B are averaged (segmental) values of the stiffness of bodies of vehicles A and B.

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4. Methods of determining the average deformation

Several methods were considered to determine the average deformation in the area of vehicle contact during the collision. In result of some necessary transformations and with an assumption having been adopted that the spring elements in the vehicle deformation zone were arranged in series, the following formulas were derived from equations (6):

$$k_A = k_B * \frac{\Delta C_B}{\Delta C_A} \tag{7}$$

$$k_B = k_Z * \left(\frac{\frac{\Delta C_B}{\Delta C_A}+1}{\frac{\Delta C_B}{\Delta C_A}}\right);\ k_Z = \frac{\Delta F_D}{\Delta C} \tag{8}$$

where:

k_Z represents equivalent stiffness determined from the force vs deformation curve characterizing the combined deformation of both vehicle bodies (Fig. 5).

The computation of the segmental values of the stiffness of bodies of vehicles A and B from equations (7) and (8) was based on the estimation of deformations of vehicle bodies. Usually, the vehicle body deformation values can be determined within the analysis and reconstruction of an accident. Therefore, an assumption was made that:

$$\frac{\Delta C_B}{\Delta C_A} = \frac{C_{B śr}}{C_{A śr}} \tag{9}$$

where:

$C_{\mathrm{A}śr}$ and $C_{Bśr}$ represent the average values of deformation of individual vehicle bodies.

The methods taken into consideration to determine the average deformation of bodies of vehicles A and B were denoted as follows:

- M1 – The average vehicle body deformation values are determined for the whole areas of deformation of the bodies of vehicle A and vehicle B.
- M2 – The average value of deformation of the body of vehicle A is determined for the belt circumscribing its bumper; for vehicle B, it is calculated for the door panel area.
- M3 – The average vehicle body deformation values are determined for the areas of vehicle deformations corresponding to each other, i.e. for vehicle A, this area is the belt defined by the front bumper and for vehicle B, it is the belt at the height of the impacting vehicle's bumper, with its length being equal to impacting vehicle's width.
- M4 – The average vehicle body deformation values are determined for a rectangle in the central part of the area of vehicle contact during the collision, with the rectangle width being equal to 30 % of the width of the vehicle deformation zone and its height being equal to the height of the front of the impacting vehicle.
- M5 – The average vehicle body deformation values are determined for a rectangle as it is in the M4 method, but the rectangle width and height are equal to 50 % of the corresponding dimensions adopted in the M4 method.
- M6 – This method is based on the calculation of the volumes of deformation of vehicles A and B in the areas whose locations correspond to each other; the said volumes are calculated by multiplying the area of the rectangle of the M5 method by the average deformation value of the M5 method.

It should be added here that the defining of the areas as specified above actually means a reasonable limitation of the extent of the deformation depth measurements to the areas on both vehicles that correspond to each other and that are characterized by considerable deformation depths. The approximate contours of the areas on which the average vehicle body deformation values were determined for vehicles A and B with using individual computation methods have been outlined in Fig. 6.

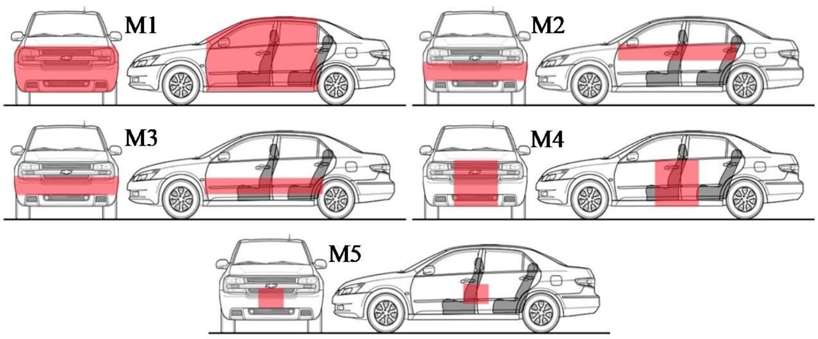

Figure 6. Areas of calculating the average deformation of the A and B vehicle bodies in accordance with methods M1-M5.

In each of the areas taken for the calculations, at least 5 points are selected where the deformation depth is measured, from which the arithmetic average values $C_{Aśr}$ and $C_{Bśr}$ of deformation of the A and B vehicle bodies are calculated.

5. Estimation of the side stiffness of a vehicle body

The NHTSA crash test results used in this work include, *inter alia*, results of measurements of post-impact deformation of vehicles A and B. Based on this, the average values of deformation of the A and B vehicle bodies, i.e. $C_{Aśr}$ and $C_{Bśr}$, respectively, were calculated in accordance with methods M1-M6 and then the vehicle body stiffness values were determined from equations (7) and (8).

The use of the deformation characteristics shown in Fig. 2 was also considered. The characteristics of deformation of the front body parts of the impacting vehicles were approximated by a linear function and, based on this, the k_A values were determined for several deformation values, i.e. 50 mm, 100 mm, 200 mm, and 300 mm in succession. Then, the k_A values were used to compute the side stiffness of vehicle B body from the combined deformation characteristics shown in Fig. 5. This method of determining the side stiffness of vehicle B body was denoted by M7. The calculation results were summarized in Table 1.

Table 1. Average deformation $C_{Bśr}$ and side stiffness k_B of vehicle B body, calculated in accordance with individual methods under consideration

Test No	M1		M2		M3		M4		M5		M6		M7	Average deformation	Average stiffness	Standard deviation of the stiffness
	$C_{Bśr}$	k_B	$C_{Bśr}$	k_B	$C_{Bśr}$	k_B	$C_{Bśr}$	k_B	$C_{Bśr}$	k_B	$C_{Bśr}$	k_B	k_B			
	[mm]	[kN/m]	[mm]	[kN/m]	[mm]	[kN/m]	[mm]	[kN/m]	[mm]	[kN/m]	[cm^3]	[kN/m]	[kN/m]	[mm]	[kN/m]	[kN/m]
5146	152	599	292	553	230	569	304	558	348	557	14710	573	647	265	579	31
5151	188	561	356	534	292	543	379	509	441	515	14090	496	548	331	529	22
5156	191	555	256	558	356	547	385	535	450	539	25495	548	652	327	562	38
5161	166	654	315	610	315	570	308	571	370	546	32354	609	714	294	611	53

6. Analysis of the computation results

The results of computation of the vehicle body side stiffness summarized in Table 1 have been compared with each other in Fig. 7. The stiffness values calculated by very different methods and from very different crash tests do not differ very much from each other. This shows that the calculation of this stiffness can be facilitated. The highest values of the stiffness were obtained when the M1 method was used (they exceeded the average value of all the calculation results by 4 %). On the opposite end, the lowest values, lower by 5 % than the average, were obtained from methods M5 and M6. The standard deviation, determined from 7 × 4 various results, was within the range of 4-9 % of the average stiffness value. This scatter may be explained by limited accuracy of determining the deformation value based on measurements carried out at a number of separate points. On the other hand, the force vs deformation curves are based on results of dynamic measurements and are obtained with taking into account the processes of elastic and plastic vehicle body deformation during a collision and the calculated stiffness values are determined from plastic deformations only. It should be added here, however, that data of this kind are usually the only data available when road accidents are analysed and reconstructed.

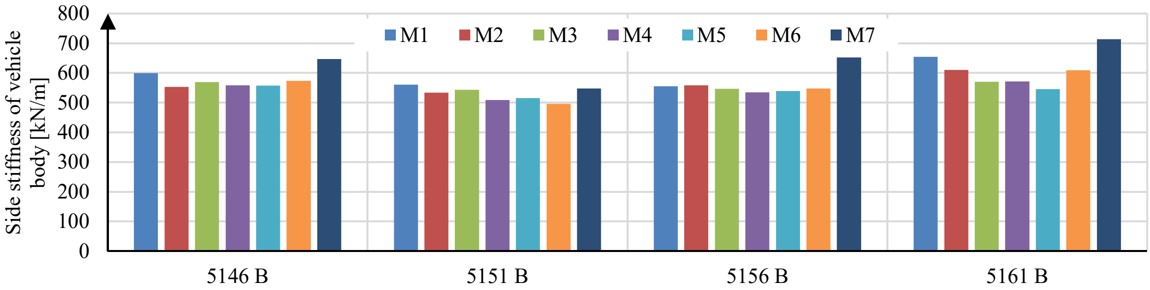

Figure 7. Comparison of the values of vehicle B body side stiffness, determined with using methods from M1 to M7.

The values of the vehicle body side stiffness calculated by the M7 method were higher by 13 % than the average stiffness values obtained by other methods. The reason may lie in the fact that in the M7 method, the values of the frontal vehicle body stiffness were taken from the force vs deformation curve plotted for a crash test where the vehicle struck a rigid barrier. In such a case, the stiffness values are higher than those recorded when the vehicle hits a deformable obstacle.

In the tests analysed where a motorcycle struck a motor car side, the car body stiffness values ranged from 750 kN/m to 1030 kN/m for the deformation range of up to 100 mm (Fig. 3). These values exceed the figures presented in Table 1 by 23-69%. This is consistent with general observations that the stiffness of a motor car body at deformations of 100-200 mm is markedly higher than it would be at bigger deformations (cf. Fig. 2). Thus, the results obtained with using different methods have a consistent nature and may be considered reliable.

7. Recapitulation and conclusions

The experimental test results used and the analytical computations carried out made it possible to determine the values of side stiffness of a motor car body by several different methods. The results obtained provide grounds for the following conclusions to be formulated:

- The average side stiffness of the body of a medium-class motor car is about a quarter less as that of the front of the car.
- The values of the side stiffness of a motor car body, calculated with using the body deformation values obtained by methods M1-M6, differ from each other by only 4-9 %.

- The popular method of using the front car stiffness value, determined from the force vs deformation curve obtained in result of a crash test with the car hitting a rigid barrier, leads to overestimating the calculated values of the side stiffness of the car body at a front-to-side collision.
- The proposed methods of determining the average deformation of the car body proved to be effective for different vehicles (SUV, van, pick-up, see Fig. 1) hitting a side of the vehicle under analysis.
- When the side stiffness of a motor car body is determined, the measurements may be focused on the central part of the deformation area; the stiffness value thus obtained will be lower by only several percent than the value calculated with taking into account the whole area of deformation of the vehicle body side.
- The possibility of focusing the measurements on the central part of the deformation area will not only facilitate the measurements but will also conduce to an improvement in the measurement accuracy.
- The side stiffness of the Honda Accord car body is approximately equal to 570 kN/m.

The values of the side stiffness of a motor car body are quite low in comparison with the frontal stiffness of the same car. This translates into the presence of a considerable hazard arising from excessive deformation of the car body side during a road accident and is reflected in the statistics of victims of the front-to-side vehicle collisions. The collected results of this research work are a source of valuable data that may be useful for the modelling of motor vehicle collisions and for any actions aimed at improving the vehicle body construction in order to raise the passive safety of motor vehicles.

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