Archives of Materials Science and Engineering

Volume 58
Issue 1
November 2012
Pages 13-21

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Analysis of material deformation work measures in determination of a vehicle's collision speed

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Received 10.09.2012; published in revised form 01.11.2012

ABSTRACT

Purpose: The article provides a discussion on the studies comprising analytical experiments conducted on material deformation work measures in determination of a vehicle's collision speed. The purpose was to analyse a deformation profile of cars whose structures included different materials using the EES calculated by different methods.

Design/methodology/approach: The investigations were conducted based on comparative analysis of methods for estimating EES for different structural materials used in vehicles. The investigation comprised 3 steps: comparison of test results obtained for frontal narrow-object impacts published by other authors, comparison of research results for frontal solid and immovable narrow-object impacts, comparison of research results for frontal aligned vehicle to vehicle collision.

Findings: Multiple materials used in a vehicle structure can affect the proper results of the EES calculated. The results confirm that structural materials influence residual deformation.

Research limitations/implications: Crash tests of real cars are very expensive. The experiments were analytical hence the impact speed was declared by the driver.

Originality/value: The results obtained imply changes of the EES calculated by different methods and for cars with different structural materials. EES is very commonly used in accident reconstructions and it may constitute the main piece of evidence in court proceedings, therefore it is very important to conduct comparative analysis of methods for estimating EES for proper vehicle structural materials.

Keywords: Automotive materials; Equivalent Energy Speed (EES); Material deformation work

Reference to this paper should be given in the following way:

R. Burdzik, P. Folęga, Ł. Konieczny, B. Łazarz, Z. Stanik, J. Warczek, Analysis of material deformation work measures in determination of a vehicle's collision speed, Archives of Materials Science and Engineering 58/1 (2012) 13-21.

PROPERTIES

1. Introduction

Safety driving is one of the most important conditions taken into account while designing and building vehicles. It should be considered to minimise the occurrence and consequences of car accidents. It can be attained by modernisation of car systems, elements and design technologies. The trend of car safety ratio increase using the possibilities of modern solutions has been depicted in Fig. 1. Authors of this paper have conducted multiple studies of a car safety system [1, 2] which, however, mainly focused on active car safety. Passive safety devices and systems are those which operate without any input or action from the vehicle user. Nowadays, it has become very popular to use new materials: high strength steel, aluminium, carbon fibre, titanium, magnesium etc. Those materials can be very effective for passive safety. There are numerous publications concerning application and testing of new materials and repair technologies in the automotive industry [3, 4, 22]. It has been proved that different materials properly used in dedicated areas of vehicle structure can perform many functions such as energy absorbers at the front and back of a vehicle or a stiff box for safety in the passenger compartment. In the front and rear sections located away from the passenger compartment, the main crush-load carrying components are located, and they are designed to absorb kinetic energy during collision. This paper presents preliminary research on a comparison of methods for estimating EES for different structural materials used in vehicles.

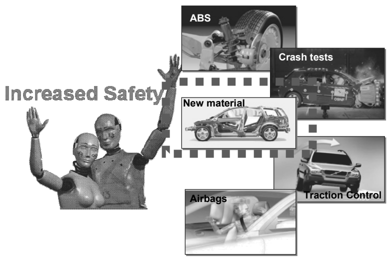

Fig. 1. Trends of car safety increase [6]

2. New materials in car structures

Customers' requirements and the transport policy force various automotive companies to build more fuel-efficient and safer vehicles. The requirements for a car body are constantly increasing (Fig. 2). In order to retain the impact energy absorbing capacity of an automotive vehicle, each body part which has the material changed should retain its impact energy absorbing capacity [4]. During a car crash, some parts in the front of the car body may undergo plastic deformation and absorb a lot of energy. The possibilities for reducing the weight of the vehicle body start with an optimised all-steel body and span all the way to an all-aluminium car. More lightweight designs can only be obtained by using fibrous composite materials. Fibrous composite materials have already started being used in passenger cars after satisfying results of their application in Formula 1. Between the extremes of all-steel and all-aluminium cars, there are solutions that combine steel with lightweight materials [5].

It is anticipated that AHSS usage in automotive bodies will climb to 50% by 2015. Automotive companies are constantly improving technologies and build vehicles from materials that offer improved user safety. The requirements for materials intended for automotive use are: easily formable, weldable, coatable and repairable. Vehicle weight reduction has been considered as one of the most important solutions to improve fuel economy. One solution to these problems is to reduce a vehicle's weight, because 57 kg weight reduction is equivalent to 0.09-0.21 km per litre of fuel economy increase [7]. It is possible that the vehicle body weight can be reduced by using multiple materials without cost increase. Lightweight automotive bodies and elements have been developed using high strength steels, aluminium alloys and composite materials. There is many research conducted on novel metallurgical technologies [20, 23-26]. The multi-material concept is that the right material types are used in the right locations for the desired product functions.

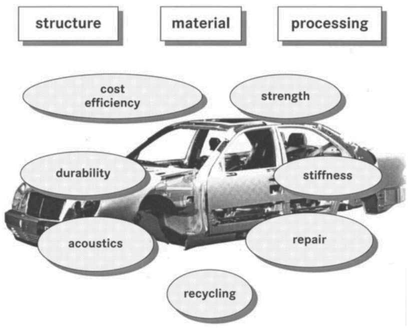

Fig. 2. Body shell requirements [5]

The first and most commonly used material is high strength steel. It has higher yield strength and failure strength than mild steel. High Strength Steel (HSS) sheets can be used in a car body to improve the components' impact energy absorbing capacity and resistance to plastic deformation. The car weight can be reduced by using high strength steel sheet of a lower depth to replace the mild steel sheet of body parts. With high strength steel sheet of higher yield strength to replace mild steel sheet, the depth of body parts sheet may be reduced with the same impact energy absorbing capacity to achieve reduction of the car weight. One of the most interesting HSS materials is Boron Steel (UHSS – Ultra High Strength Steel). The boron steel type used in the automotive industry today has extremely (ultra) high strength. It can have a yield point of about 1350-1400 MPa. The introduction of boron steel was found primarily on Porsche Cayenne SUV (2002), Boxster and Carrera (2003) and Mercedes-Benz E Class and Volvo XC90 SUV(2003). In 2004, other automotive companies started to use boron steel as well.

Perspective materials that could fulfil most of the relevant requirements include dual-phase steel. Also high manganese TWIP and TRIPLEX alloys represent new perspective material types, with high strength properties, toughness and ductility in wide temperature range and high energy absorption on impact. These materials are definitely useful in the automotive industry. The TWIP (twining induced plasticity) material is characterised by Fe-Mn-C chemical composition with low aluminium content or possibly even with limited silicon content, respectively. The TRIPLEX material (three elements besides iron) is based on Fe-Mn-C-Al with the aluminium content higher than 8 wt % and without the silicon content. [8].

The next group of materials is light metals. One may observe increasing use of metals such as aluminium and magnesium in the automotive industry. Predictions estimate a rise in aluminium's contribution to the total vehicle weight from 6% to more than 10-20% [9].

In conclusion, there are many new materials used in the automotive industry and various studies are constantly conducted on novel, perspective materials with properties that can meet the increasing requirements (Fig. 3). Such multitude of these materials cause problems related to designing and fabrication. One must analyse in which parts of the structure the appropriate materials should be used. The paper [10] presents the latest performance indices and procedures to select materials for lightweight and cost-effective multi-material automotive bodies. The mean crush load, F_m, is a widely accepted design parameter to evaluate the capability of thin-walled components to absorb crash energy. F_m is defined as the ratio of energy absorption to the deformed length. This paper provides results of a study on replacement of chosen car body parts in order to achieve car body lightweighting. An FE model of the car body is shown in Fig. 4. This FE model was obtained from the US National Highway Traffic Safety Administration (NHTSA). The body is originally made of mild steel (Mild) and Bake-Hardenable (BH) steel. Some car body part materials were replaced from mild steel sheet to high strength steel sheet without impairment of each part’s impact energy absorbing capacity. Consequently, the high strength steel sheet depth after replacement was determined. It has been depicted in Fig. 5.

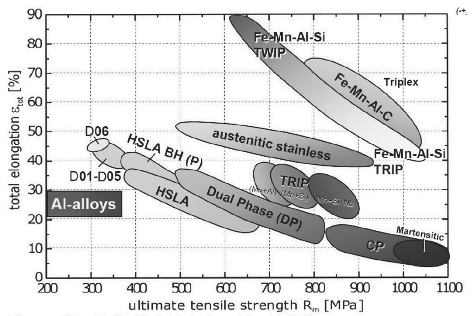

Fig. 3. Ductility and strength combinations of steel for automotive applications

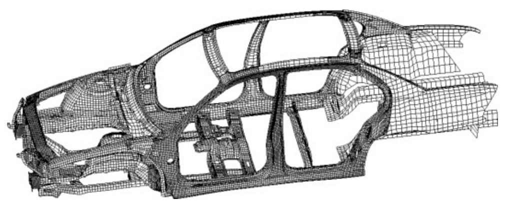

Fig. 4. Case study for a car body structure [21]

a) b)

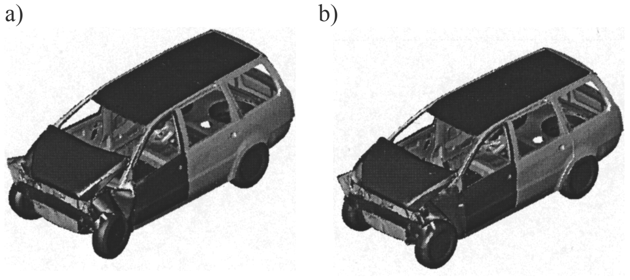

Fig. 5. Deformation of a car body of mild steel and high strength steel. a) Before material replacement, b) after material replacement [10]

3. Methods for estimating EES

There are many methods for estimating the relative velocity or delta V of two colliding vehicles at impact by simply evaluating energy loss during the collision [11]. Energy loss can be calculated by measuring residual deformations produced on the vehicle at a set of measurement stations [12,13] located on damaged parts of the car body, and by applying the vehicle’s stiffness coefficients [14]. The energy loss estimation method, based on a measurement of residual deformation, is widely used in Europe and USA. In the 1980s, Burg, Martin and Zeidler defined the notion of Equivalent Energy Speed (EES). EES is a speed measure which will be transformed into deformation energy during the collision. International Organization for Standardization (ISO/DIS 12353-1:1996(E)) define the EES as the equivalent speed at which a particular vehicle would need to contact any fixed rigid object in order to dissipate the deformation energy corresponding to the observed vehicle residual crush.

The plastic deformation energy of a damaged car is expressed as kinetic energy of the car with the virtual velocity value of EES. For an authentic EES estimation, various crash tests with different conditions are necessary because the energy absorption depends on various parameters.

$$EES = \sqrt{\frac{2 \cdot W_{def}}{m}} \quad \left[\frac{m}{s}\right] \tag{1}$$

where:
W_{def} – deformation work [J],
m – vehicle mass [kg],
EES – Energy Equivalent Speed [m/s].

The energy deformation can be calculated from the damage measured on the vehicle using either the speed-deformation curve generated from a number of impact results at various speeds or a force-displacement curve prepared from a single impact test. The other measure that has been proposed is the Equivalent Barrier Speed (EBS). This is the speed at which a vehicle would have to strike a solid immovable block in order to cause the same damage. It is limited to head-on impacts and varied to include other types of solid object impacts when it is known as the ‘Equivalent Test Speed’ (ETS).

A car accident is always a random process, hence there are many methods for estimating EES. Some of those were used in the analytical experiments.

NTSB equation method. National Transportation Safety Board (NTSB) is an independent federal agency issuing safety recommendations aimed at preventing future accidents. The method proposed by NTSB is based on results of tests of vehicle impacts with a pole. The EES is determined by the following equation:

$$EES = BPO + BP1 \cdot C_{max} \ [km/h] \tag{2}$$

where:
BPO – speed at which no crush is expected, velocity depended on the vehicle weight (tabular data),
BP1 – slope of speed versus crush, velocity changes according to the function of deformations (tabular data),
C_{max} – maximum of vehicle deformation.

Morgan and Ivey's method based on equation [15]:

$$EES = 0.036 \cdot C_{\max} \cdot \sqrt{\left(395 - 0.14 \cdot m_p\right) \cdot \left(1 + \Lambda E\right)} \quad [km/h] \tag{3}$$

where:
C_{max} – maximum depth of vehicle deformation,
m_p – vehicle weight,
ΔE – relative change (increase or decrease) of energy absorber in crushing the vehicle by impacting the pole.

Nystrom's and Kost's method is based on an equation published by the authors in 1992 in a SAE paper [16]. Using 19 staged frontal pole barrier crash tests, they evaluated methods for relating pre-impact speed to residual crush. The Nystrom and Kost equation is expressed as follow:

$$EES = 5 + [0.964 - (0.0000351W)] \cdot C_{max} \ [km/h] \tag{4}$$

where:
W – vehicle weight,
C_{max} – maximum of vehicles deformation.

The expression in brackets is a representation of BP1 (it depends on the weight and power transmission axis localisation), Craig method. Victor Craig examined the other aforementioned equations and compared their results with a generalisation which suggested that the depth of maximum static crush is approximately equivalent to the impact speed of the vehicle [17]. The equation is:

a) For the vehicles with front drive and length under 4.6 [m] and weight under 1360 [kg]:
for: $C_{max} \leq 30.5$ [cm] $EES = 0.3 \cdot C_{max} + 6.4$ [km/h]
$C_{max} > 30.5$ [cm] $EES = 0.82 \cdot C_{max} - 9.7$ [km/h]

b) For larger vehicles with front or rear drive:
for : $C_{max} \leq 46$ [cm] $EES = 0.34 \cdot C_{max} + 6.4$ [km/h]
$C_{max} > 46$ [cm] $EES = 0.75 \cdot C_{max} + 11.3$ [km/h]

where C_{max} – maximum of vehicle deformation.

Method of coefficient *k*. Coefficient *k* is the unit stiffness of vehicle structure. It is one of experimental coefficients used by General Motors Corporation research teams during tests of vehicle impacts with solid and immovable objects. The deformation work is determined by equations:

$$W_{def} = \frac{1}{2} \cdot b \cdot h \cdot k \cdot f_{trw}^2 \quad [Nm] \tag{5}$$

where:
b – width average of deformation,
h – height average of deformation,
f_{trw} – plastic deformation.

The data acquired from crash tests are processed to obtain the stiffness coefficients according to the hypothesis of linear approximation of the force-crush curve. Obviously, these coefficients, due to the manner in which they are determined, are suitable for describing the vehicle's structural behaviour only for the specific type of impact in question, that is front, rear or side impact. The researchers constantly propose new methodologies for correctly estimating the energy absorbed in an oblique impact, using the stiffness coefficients A and B and taking different directions of the forces and deformations occurring during collision into consideration.

The CRASH 3 method estimate the impact velocity and the Delta-V of a vehicle in a crash based on the information from the vehicle and the crash scene. CRASH3 is updating program by adding stiffness coefficients of vehicles. The energy is calculated by measuring the residual crush of the vehicle and applying an estimate of the stiffness to the crush area measured. Stiffness categories contain stiffness coefficients that define a linear force-deflection curve for a specific vehicle category (mini, compact etc).

4. Comparative analysis of methods for estimating EES for different structural materials used in vehicles

The investigations were conducted based on a comparative analysis of methods for estimating EES for different structural materials used in vehicles. These investigation comprised 3 steps:

- comparison of test results for frontal narrow-object impacts published by others authors,
- comparison of results obtained in tests of frontal solid and immovable narrow-object impacts,
- comparison of results obtained in tests of frontal aligned vehicle to vehicle collision (straight line centric impact).

The residual deformation measurement techniques are generally suitable for describing physical phenomena, and the correct measurement method is strictly defined in order to group all of the real cases under three classes: front, rear and side impact [11].

In order to compare the methods for estimating EES for frontal solid and immovable objects and to analyse the influence of structural materials of vehicles, analytical experiments were conducted based on chosen test results obtained by Joseph N. Cofone, Andrew S. Rich and John C. Scott presented at the Joint Conference in 2003 and IPTM Special Problems in 2007 tests [18]. The results obtained have been presented in Tables 1-4 and Figures 6-13 below.

Fig. 6. Deformation of Oldsmobile Cutlass 1978, impact speed of 45 km/h, maximum deformation of 0.64 m [18]

Table 1.
Comparison of calculated EES – Oldsmobile Cutlass 1978

Method Equation	EES/EBS [km/h]	Difference of average speed [%]	Difference of impact speed [km/h]
NTSB	35.08	13.66	-9.98
Morgan and Ivey	36.85	9.31	-8.21
Nystrom and Kost	46.83	15.25	1.77
Craig	43.77	7.72	-1.29
Average speed	40.64	-	-4.43
Impact speed	45.06	10.89	-

Table 2.
Comparison of calculated EES – Chevrolet Celebrity 1986

Method Equation	EES/EBS [km/h]	Difference of average speed [%]	Difference of impact speed [km/h]
NTSB	32.99	12.95	-16.09
Morgan and Ivey	35.73	5.73	-13.36
Nystrom and Kost	42.97	13.38	-6.12
Craig	39.91	5.31	-9.17
Average speed	37.90	-	-11.18
Impact speed	49.08	29.51	-

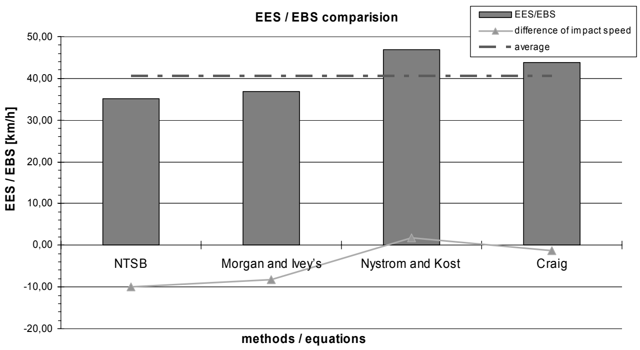

Fig. 7. Distribution of EES values and differences of impact speed for Oldsmobile Cutlass, impact speed of 45 km/h

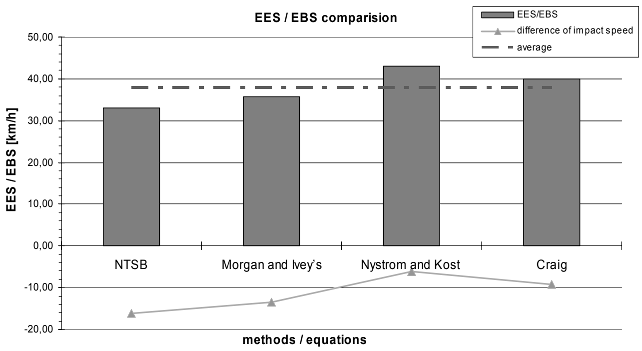

Fig. 9. Distribution of EES values and differences of impact speed for Chevrolet Celebrity, impact speed of 49 km/h

Fig. 8. Deformation of Chevrolet Celebrity 1986, impact speed of 49 km/h, maximum deformation of 0.55 m [18]

Fig. 10. Deformation of Ford Escord 1989, impact speed of 47 km/h, maximum deformation of 0.43 m [18]

Table 3.
Comparison of calculated EES – Ford Escord 1989

Method Equation	EES/EBS [km/h]	Difference of average speed [%]	Difference of impact speed [km/h]
NTSB	29.61	9.69	-17.06
Morgan and Ivey	30.90	5.77	-15.77
Nystrom and Kost	37.34	13.87	-9.33
Craig	33.31	1.60	-13.36
Average speed	32.79	-	-13.88
Impact speed	46.67	42.33	-

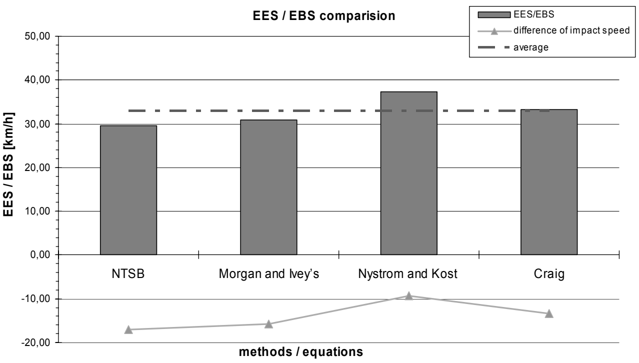

Fig. 11. Distribution of EES values and differences of impact speed for Ford Escord, impact speed of 47 km/h

Fig. 12. Deformation of Ford Taurus 1999, impact speed of 78 km/h, maximum deformation of 0.39 m [18]

Table 4.
Comparison of calculated EES – Ford Taurus 1999

Method Equation	EES/EBS [km/h]	Difference of average speed [%]	Difference of impact speed [km/h]
NTSB	69.85	1.17	-8.21
Morgan and Ivey	69.36	1.85	-8.69
Nystrom and Kost	72.58	2.70	-5.47
Craig	70.89	0.31	-7.16
Average speed	70.67	-	-7.38
Impact speed	78.05	10.45	-

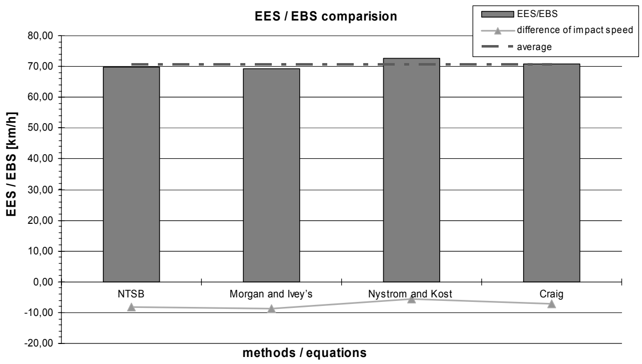

Fig. 13. Distribution of EES values and differences of impact speed for Ford Taurus, impact speed of 78 km/h

Normal energy loss is calculated by a discrete number of residual crush measurements in the direction parallel to the vehicle's axis using the stiffness coefficients or different methods. In the results published by Joseph N. Cofone, Andrew S. Rich and John C. Scott, there is information about maximum deformation only. The other analytical experiment was based on own research results. The profile of deformation in multiple points was measured on the vehicle after frontal solid and immovable narrow-object impact. It has been depicted in the Figure 14 below. The deformation profile has been specified in the Table 5 below. The damage profile measurement methodology has been discussed in [19].

A complex analysis of methods for estimating EES for this research was discussed in [6]. Table 6 presents chosen results for a comparison with Tables 1-4. The distribution of EES values and differences of impact speed for the methods compared have been depicted in Fig. 15.

The third case studied was a vehicle to vehicle collision. A deformation profile measurement and some analytical calculations were conducted (Fig. 16, Tab.7). For this kind of impact, different methods for estimating EES should be used. The results obtained have been provided in Tab. 8 and depicted in Fig. 17.

Fig. 14. Deformation of Hyundai Accent 1995, impact speed of 16 km/h, maximum deformation of 0.31 m

Table 5.
Profile of deformation measurement – Hyundai Accent 1995

Vehicle deformation		
Width of deformation [m]		0.25
Height average of deformation [m]		0.4
Depth of deformation [m]	C_1	0.14
	C_2	0.18
	C_3	0.20
	C_4	0.23
	C_5	0.27
	C_6	0.31
Average depth of deformation [m]		0.22

Table 6.
Comparison of calculated EES – Hyundai Accent 1995

Method Equation	EES/EBS [km/h]	Difference of average speed [%]	Difference of impact speed [km/h]
NTSB	17.44	5.93	1.44
Morgan and Ivey	16	13.70	0.00
Nystrom and Kost	25	34.84	9.00
Craig	15.72	15.21	-0.28
Average speed	18.54	-	2.54
Impact speed	16	13.70	-

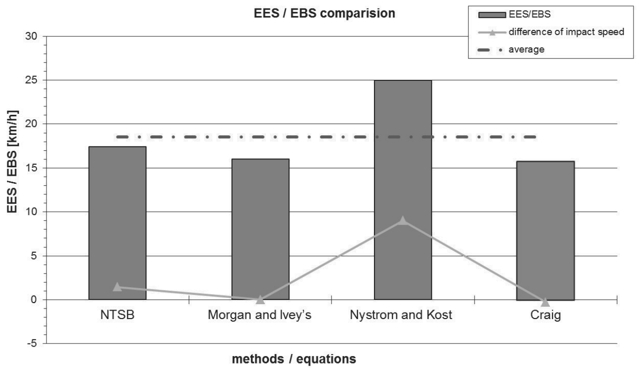

Fig. 15. Distribution of EES values and differences of impact speed for Hyundai Accent, impact speed of 16 km/h

Fig. 16. Deformation of Seat Cordoba 1997, impact speed of 18 km/h, maximum deformation of 0.26 m

Table 7.
Deformation profile measurement – Seat Cordoba 1997

Vehicle deformation		
Width of deformation [m]		0.75
Height average of deformation [m]		0.4
Depth of deformation [m]	C_1	0.09
	C_2	0.17
	C_3	0.22
	C_4	0.26
	C_5	0.24
	C_6	0.16
Average depth of deformation [m]		0.20

Table 8.
Comparison of calculated EES – Seat Cordoba 1997

Method Equation	EES/EBS [km/h]	Difference of average speed [%]	Difference of impact speed [km/h]
Coefficient *k*	15.48	4.18	-2.52
McHenry and Marquard – CRASH 3	16.83	4.18	-1.17
Average speed	16.155	-	-1.85
Impact speed	18	11.42	-

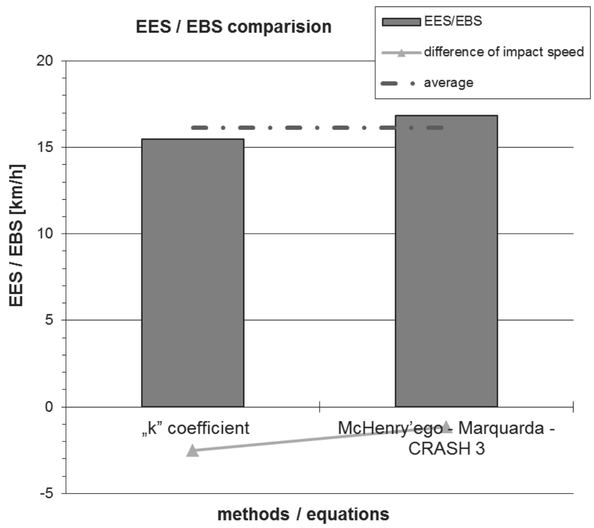

Fig. 17. Distribution of EES values and differences of impact speed for Seat Cordoba, impact speed of 18 km/h

5. Conclusions

Material deformation work measures are very commonly applied to determine a vehicle's collision speed in accident reconstructions. The EES estimating methods mainly use the complete vehicle stiffness value. Various materials used in a vehicle structure can affect the proper results of the EES calculations. The results discussed in the paper evidence how significantly structural materials influence the residual deformation. The study in question should be continued using the latest methods with the selected material properties and coefficients.

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