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On the influence of the acceleration recording time on the calculation of impact severity indexes

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Abstract. The paper concerns with the analysis of normative requirements pertaining to experimental setup of a crash test and its numerical modelling. An overview of parameters describing the collision of a vehicle with a road restraining system is presented. A short description of a concrete road safety barrier is presented. A brief description of numerical modelling procedures for crash tests is given as well. The parametric influence analysis is performed of the acceleration recording time on various crash test functionality parameters The simulations are carried out using LS-DYNA finite element code with a solver version R.8.1

1 Introduction

In January 2011 European Standards EN 1317 became mandatory in all countries within members of CEN (European Committee for Standardization) [1, 2]. Next year, in January 2012, guidelines for computational mechanics of crash testing were published, where basic validation procedures were specified [3, 4]. These documents defined several levels of performance for the barriers. There are three main criteria: the containment level, the impact severity levels and the deformation expressed by appropriate parameters. To qualify road safety barrier to an appropriate containment level a corresponding crash test must be performed on the basis of European Standards [2]. Another criterion is impact severity level which is described by two parameters: ASI (*Acceleration Severity Index*) and THIV (*Theoretical Head Impact Velocity*). The last criterion is the deformation of road restrained system. This paper is focused on the applicability of the data collection requirement for the calculation of ASI and THIV parameters for the numerical model post-processing.

The study presents a shortened description of characteristic parameters for crash tests specification in section 2. Section 3 contains general information of the vehicle and concrete barrier used in full-scale experimental crash test. Furthermore, a brief description is given of the procedure of crash test numerical modelling using LS-Dyna [5-6] finite element code. Parametric analysis was performed to check the influence of the travel time of the vehicle before impact on the calculation of ASI, THIV parameters. The results are presented in section 4.

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2 Characteristic parameters for the crash tests specification

2.1 Acceleration Severity Index (ASI)

According to European Standards [1] every vehicle, used for the calculation of ASI and THIV, shall contain at least three accelerometers for measurement in three global directions and optionally an angular velocity sensor. The accelerometers shall be mounted at a single point placed in the nearby of the vehicle's centre of mass. Calculation of ASI parameter is not required for Heavy Goods Vehicles (HGV) or buses, although, during full-scale crash test such data can be collected for the purpose of validation of the numerical model. The idea of ASI parameter is to bring the measure of motion severity for a person inside the vehicle during collision with road restrained system. Acceleration components are filtered with four-pole phase less Butterworth low-pass digital filter, detecting a cut-off frequency of 13 Hz. The ASI parameter is assumed as a single, maximum measure of the data collected during collision, according to the formula $ASI = \max[ASI(t)]$.

2.2 Theoretical Head Impact Velocity (THIV)

Another functional parameter calculated in crash test description is the Theoretical Head Impact Velocity (THIV). The concept of this parameter was to assess the possible amount of damage dealt to occupant inside the vehicle during collision with road vehicle restraint systems. It is assumed that at the moment of impact both, the vehicle and occupant's theoretical head show an identical horizontal velocity. After impact, the velocity of this theoretical cabin is calculated integrating accelerations in x and y directions. The vehicle's yaw angle can be measured using angular velocity collected by an appropriate sensor. Technically (in numerical simulations), accelerometers are modelled by rigid parts collecting all the required nodal data. According to European Standards [1] the limit value for the THIV parameter for all acceptable impact severity levels is 33 km/h.

2.3 Deformation

There are couple measures for the description of the road safety barrier deformation. They vary depending on a type of the vehicle. The first functional parameter is working width. It describes the maximum lateral distance between undeformed guideway and maximum dynamic position of any part of the barrier which was not detached during collision. If a vehicle deforms around barrier and it is not possible to interpret the working width correctly it is allowed to take the maximum lateral position of any part of the vehicle as an alternative. Another parameter is dynamic deflection which shows the maximum lateral dynamic displacement of any point of the traffic face (guideway) of the road restraint system. The last parameter is used only for certain types of vehicles i.e. HGVs and buses. This parameter is the vehicle intrusion. It shows maximum dynamic, lateral position of the vehicle from the undeformed traffic side. Besides those parameters, the general view of the permanent deformation should be shown.

In the upcoming part of the paper working width and dynamic deflection will be referred to as the performance parameters.

3 Description of the concrete road safety barrier

3.1 Geometry and specification

Road safety barriers are used to re-direct vehicles deviating from the road or to prevent dangerous breakthrough events. In the places where significant damage cannot be allowed road restrained systems with higher containment levels are used. As an example high containment level concrete barrier protecting bridge column is presented in fig. 1. Concrete barriers were developed to produce stiff response of the road restrained system i.e., energy dissipation with relatively small transverse displacement. The main concept is to convert energy of the impact into frictional sliding energy due to high friction coefficient between the barrier and the basis. The analysed barrier is composed of single elements, called segments. It weighs 4 tonnes and is 8 m long. The segments are connected using coupling elements which work as an interlock construction. Ultimately, the barrier works as a single chain, restraining vehicles during collision. The minimal length of permanent barrier installation is 80 m. This requirement does not apply to the temporary barrier which is a subject of the work.

Fig. 1. Concrete barrier protecting the bridge column (source: www.debonte.com).

3.2 Brief description of finite element model

3.2.1 Vehicle model

Numerical model of HGV consists of 32405 nodes. This model was adapted from [7] and subjected to minor modifications in order to remove some noticed numerical instabilities. Two accelerometers were placed in the model: the first in the centre of mass and second on the dashboard of the vehicle. The placement of the second accelerometer corresponds to the placement during full-scale crash test. The car's numerical model with both accelerometers is shown in fig. 2.

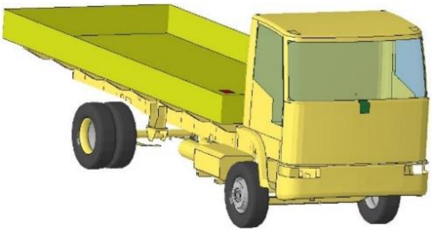

Fig. 2. Heavy Goods Vehicle numerical model. Accelerometers are marked with green and red colour.

3.2.2 Segment of the concrete barrier model

An important aspect of numerical model preparation was to recreate the exact reinforcement placement as it is the key in steel - concrete interaction modelling. The finite element mesh for the concrete part consists of 4-node 3d solid elements based on tetrahedron shape. Steel coupling parts were meshed using hexahedron solid elements. Both solid element types show constant stress across the closed volume with one point integration rule. Steel reinforcing bars were modelled using Hughes-Liu beam elements with integration over cross section. The reinforcement used in barrier segment has diameter of 10 and 20 mm while the stirrups have diameter of 8 mm. Interaction between reinforcement and concrete was modelled by constraining beam elements in solid structure [5, 6]. The method used in modelling does not require reinforcement nodes to coincide with concrete mesh. In order to describe the complex behaviour of the concrete finite element mesh with high density is needed and additionally advanced material law should be used e.g. [8, 9]. Therefore, calculation time for concrete barriers is longer when compared to the steel barrier. However, the material law used in this research includes a feature, that reduces the mesh size sensitivity, [8, 9] based on the calculated fracture energy. Additional simulations were carried out to investigate the influence of the mesh size on the stress distribution. Thus, based on these results and in order to reduce the calculation time two different finite element mesh densities were applied. A more detailed mesh consists of 46004 nodes and 210074 finite solid elements. It is used in a region of a direct impact. More coarse mesh was constructed from 9099 nodes and 22027 tetrahedron solid elements and was used in remaining segments. Mesh details of the quarter of the segment can be found in fig. 3.

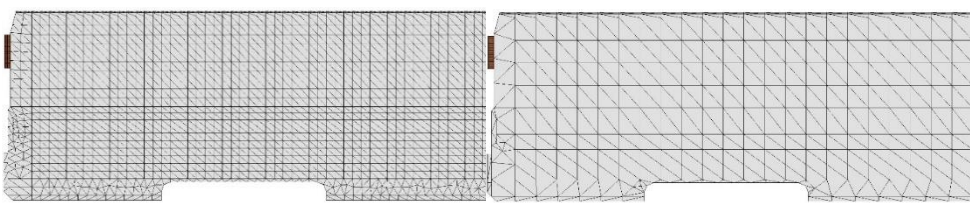

Fig. 3. Finite element mesh details for the quarter of the concrete barrier segment (segment 3 on the left and remaining segments on the right, see fig. 6).

3.2.3 Crash test assembly

Concrete road safety system consists of six segments. Segments are anchored to each other using coupling parts. There is a 5 mm gap between concrete segment faces. The segments are placed freely on the ground shell surface. Coulomb friction was specified using penalty based LS-DYNA's contact impact algorithm [5, 6]. Full length of the road restraining system is 46 m and the total weight is 24 tonnes. A vehicle weight of approx. 10 tonnes is placed at a varying distance from the fixed impact point. The angle between the velocity vector and the barrier axis is 8 degrees. Two views of the simulation model are shown on fig. 4. A detailed friction modelling was performed as it is a key factor for interaction between various types of materials.

Crash test simulation, described in the paper is based on full-scale crash test experiment made in Research Institute for Protective Systems (Inowrocław, Poland). It was performed as the part of the national programme aimed at the improvement of the safety of the roads in Poland [10]. Numerical simulations were carried out using finite element code with explicit time integration. This method is widely used in modelling vehicle collision against various types of road restrained systems [11-14]. Validation procedures have been described in European Standards [3,4], their direct use can be found in [15,16]. Validation of the concrete road safety barrier was performed showing that the obtained numerical response is correct. Therefore, the parametric analysis was conducted.

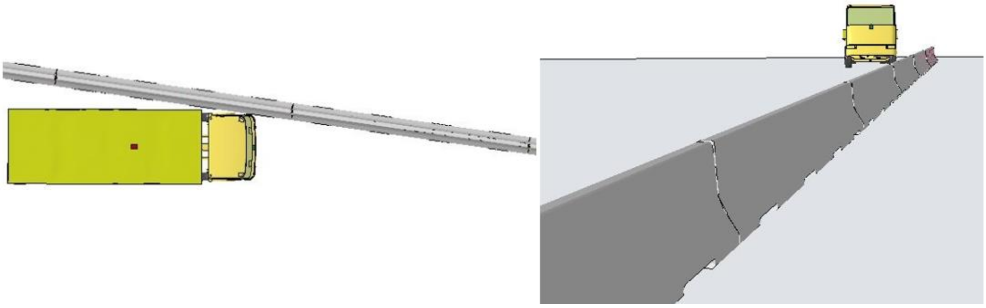

Fig. 4. Different views of the research ground with the vehicle and the barrier

4 Parametric analysis

4.1 Description of the analysis

Parametric analysis was carried out to assess the influence of the offset distance of the vehicle from the barrier on calculating impact severity indexes for numerical simulations. The general idea of the study was to confront normative requirements [1-2] for the full-scale crash tests with results obtained from numerical simulation. According to standard [1-2] to capture the information required in full-scale crash tests reports the duration time of the analysis should be at least approx. 2 seconds. The calculation time using 9 cores of the typical personal computer would take approx. 72 hours, doubling the number of cores to 18 yields a drop in calculation time to 48 hours. Taking into account the computation of concrete barrier 88 meters long the problem of available resources is significantly increasing. In order to decrease computation time it is necessary to exclude some elements of the model that may be assumed negligible. In [1] it is said that: *"Since the data will be filtered by recursive (Butterworth) filters, more data should be collected than is specifically required by the analysis. A recursive filter always produces "starting transients" at the beginning and end of the data, and requires time to "settle down". An additional 500 ms of data shall be collected at the beginning and end of the data; this extra data can then be discarded after filtering"* [1, pp.13]. According to this requirement crash test simulation should last additional second. Application of this requirement has adverse effect on the computation time. Therefore, it was found that the influence of the additional data collection time on computing impact severity indexes is worth investigating.

It was noticed that after setting initial velocity of the vehicle to the prescribed value, after some time, there is a drop of the initial velocity. Despite that there is no friction caused by air there are still energy dissipation due mutual interaction among parts of the model. Basing on the results obtained from simulations it was assumed that the impact of this factor is negligible. The variation of velocity when the actual impact occurs is less than 1 km/h. All the data can be seen in fig. 5. The graph presents curves for five different acceleration recording times before impact. Values at the intersection with the ordinate axis indicates velocities at the moment of impact. The curves were calculated with the accelerometer mounted in the middle of the vehicle's dashboard. All the data shown in fig. 5 was filtered with the Butterworth filter with the cut-off frequency 20 Hz build in Ls-PrePost software.

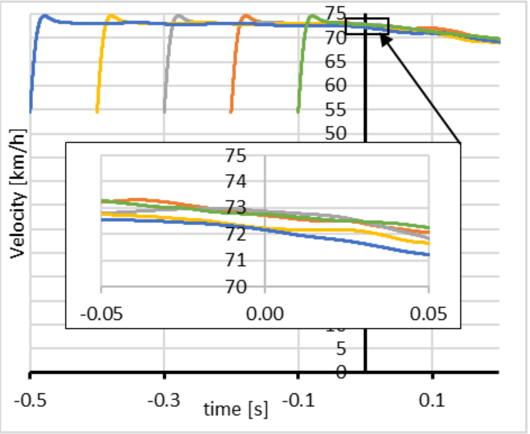

Fig. 5. Velocity in a function of time for different offset distances of the vehicle.

4.2 Results

The results were obtained for five different models. The only difference in the model input was the variable recording time of the acceleration data. The differences between crash tests results were found. They are probably due to complexity of the numerical modelling of the crash tests events. The explicit time integration method was used for time integration. It is known that this method causes errors to accumulate during the numerical integration in the time domain. Other deviations may occur due to the placement of the vehicle's centre of mass. This factor causes the wheels of the vehicle to turn over time. All the mentioned factors also contribute in the process of using the contact algorithm which may cause another differences in acquired results.

All of the five simulations show similar course, the differences are relatively small. Performance parameter values for concrete road safety barrier have been summed up in table 1. Depending on the offset distance the values slightly vary. Differences of the ASI and THIV parameters are more likely to be observed than in the working width (W). The difference probably is due to their calculation methods. ASI and THIV parameters are calculated directly from the data acquired from accelerometer. During simulation a whole vehicle vibrates, oscillates and this may lead to slight differences. On the other hand, working width is a resultant from all the model parts interaction, combined together. ASI parameter in most cases is equal to 0.4. Only the first case shows the ASI equal to 0.5. This difference may be caused by difference in the actual impact velocities. THIV was calculated, inter alia, from the angular velocity of the accelerometer. The higher values of the THIV (13-14 km/h) were observed when the wheels were turned left. Two cases, with the THIV parameter equal to the 12 km/h, had the wheels that remained straight.

The deformation of the system vary as much as +/- 4 cm. These variations may be attributed to the differences in used processors, approximations during time integration loop and others. All the information about the methods used in modelling and their limitations are contained in a book about theory used in LS-DYNA software [5]. Convention of the segments numbering for the concrete barrier H2/W5/B numerical model is shown in fig. 6. In the table 2 there is a summary of the static working width measures. The dynamic deflection values can be obtained by subtracting the width of the barrier from the static deformation values of certain positions. Fig. 7 presents the graph with static deformation's envelop on it. As it can be seen the maximum variation of the deformation is equal to 4 cm. Comparing this value to the length of the segment or it's width the ratio is equal to 1% and 7 % respectively.

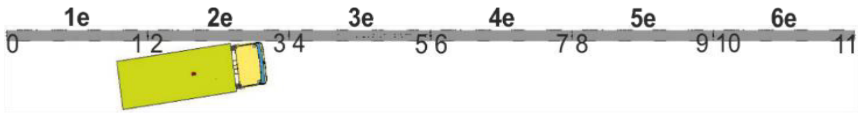

Fig. 6 Convention of the segments numbering

Table 1. Summary of functionality parameter values.

Collection time for additional data [s]	ASI [-]	THIV [km/h]	W [m]
0.1	0.45 (0.5)	13.7 (14)	0.91 (0.9)
0.2	0.40 (0.4)	12.0 (12)	0.93 (0.9)
0.3	0.44 (0.4)	13.1 (13)	0.93 (0.9)
0.4	0.4 (0.4)	13.5 (14)	0.89 (0.9)
0.5	0.38 (0.4)	11.9 (12)	0.92 (0.9)

Table 2. Static deformation for different collection times.

Collection time for additional data [s]	0.1	0.2	0.3	0.4	0.5	
Connection nr/ Element nr	Static deformation [cm]					Difference +/- [cm]
0	43	42	42	44	43	2
1E	56	55	54	54	55	2
1	68	67	66	64	67	4
2	68	67	66	64	67	4
2E	79	80	79	76	79	4
3	90	92	93	89	91	4
4	90	93	93	89	91	4
3E	88	91	91	89	88	3
5	83	86	86	85	83	3
6	83	86	86	85	83	3
4E	69	71	73	71	70	4
7	56	57	59	57	58	3
8	56	57	59	57	58	3
5E	56	55	55	56	56	1
9	55	53	51	55	54	4
10	55	53	51	55	54	4
6E	56	56	56	56	56	0
11	57	59	61	57	58	4

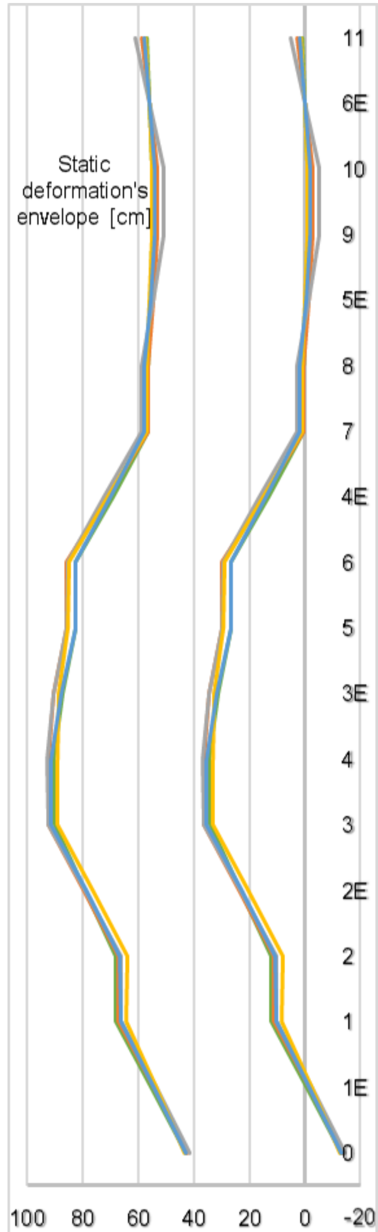

Fig. 7. Static deformation's envelope for different data collection times.

5 Conclusions

Based on the presented results the following conclusions may be drawn:

- The time necessary for the vehicle to approach the barrier has the influence on the actual impact velocity. This in turn causes the differences of the crash parameters values. However, basing on presented results, the influence of the additional acceleration data collection times on the calculation of impact severity indexes and other functionality parameters can be assumed negligible.
- Calculation time, as the key factor in explicit analysis, is strongly dependent on the mesh size. Therefore, the influence of the element size on the stress distribution must be investigated. In the analysed example case, based on full-scale test results, usage of segments element size approx.. 100 mm along with application of the fine meshed segment (el. size approx.. 38mm) in the place of direct impact provided sufficiently accurate results.

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