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DYNAMIC TESTS OF THE CULVERT FACE WITHIN CRASHTESTS

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Abstract. Severity of a vehicle impact into solid obstacles alongside the road can be annually illustrated through accident statistics. One example of such solid obstacles is drainage ditch culvert faces. Within the research at the Faculty of Transportation Sciences of the Czech Technical University new equipment has been designed in a form of a modular system of the drainage ditch culvert faces construction. The qualities of this equipment have been tested by means of crash tests with a passenger vehicle Škoda Fabia making use of criteria of biomechanical endurance of the vehicle passengers. The results have been compared with the test carried out by means of a vehicle crash into concrete culvert faces.

Keywords: Drainage ditch, vehicle crash, occupant safety, deformation block, crash test, acceleration.

1. Introduction

The objective of this article succeeding the already published primary research "Access Bridge Design Measures for Safety Increase of the Road Infrastructure" is to prove efficacy of the designed deformable structure of the drainage ditch culvert faces by means of a crash test.

The requirements for qualities of a deformable item for the stated application are specific and they thus differ from the so far patented solutions [1–5].

It is first and foremost the requirement for deformation quality in the direction vertical to axes of honeycombs (cells), sufficient capacity in the direction of honeycomb axes and also high durability that will be guaranteed by means of high-early cement mixtures or composites [6].

When crashed, the internal structure of the deformable block will be distorted in a controlled way, thus the vehicle is going to be gradually decelerated. The internal structure of the deformable block should effectively dissipate kinetic energy only by means of a vehicle speed reduction, i.e. the kinetic energy of the vehicle is not primarily used for the deformation of safety zones of the vehicle [7]. At the same time the deformable block has sufficient firmness in the vertical direction to axes of the cells and can shift a load from axletree pressure.

2. Crashtests

For proving the utility of the deformation structure of drainage ditch culvert faces a crash test of a passenger vehicle under the nominal speed of $50\,\mathrm{km{\cdot}h^{-1}}$ was carried out, when the vehicle crashed vertically into a drainage ditch culvert face located in the road drainage ditch when the last 5 meters in front of the very crash place (due to the necessity to reiterate the tests and to compare better the results) the tested vehicle was moving at constant speed parallelly with the axis of the ditch.

In order to be able to compare the results, 2 crash tests were carried out (Figure 1 and 2):

- Test No. 001 – passenger vehicle M1 × drainage ditch with an integrated deformation zone.
- Test No. 002 – passenger vehicle M1 × drainage ditch of a classical construction (concrete face).

2.1. Parameters of the drainage ditch

- Outside dimensions (length/width/height): 3.2/2.4/0.95 m,
- weight: 5,500 kg,
- parameters of the ditch for steering of the vehicle: width 1.9 m, depth 0.75 m.

Considering that it was a working prototype, and the primary purpose of the test was a dynamic test of the deformation material used, the culvert face was not equipped with a drainage pipe.

2.2. Testing vehicles

Two Fabia vehicles of the following parameters were available [8]:

- unladen weight: 1,055 kg,
- size (length/width/height): 3.99/1.73/1.47 m,
- wheel base: 2.47 m,
- tread: 1.46 m,
- inner height: 0.13 m.

The vehicle was for each crash test equipped with dummy H III 50 % (77 kg) in the place of a driver (seating position 1.) and dummy P6 (22 kg) in the children vehicle restraint system in the back seat right behind the driver (seating position 4.). Triaxial accelerometer was placed during each test on the body

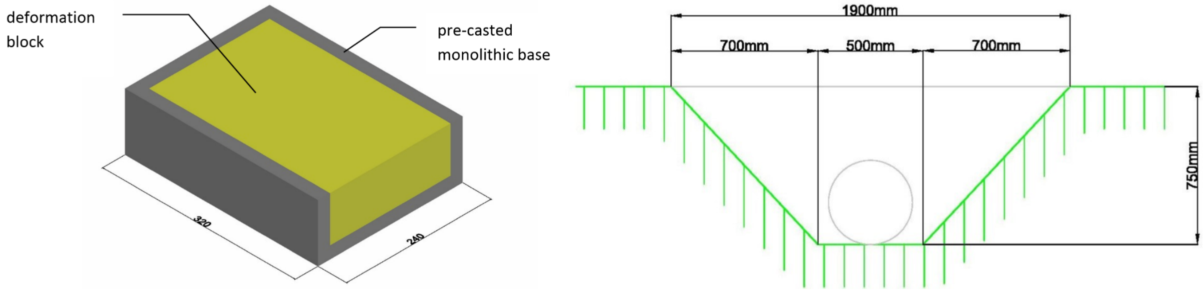

Figure 1. Deformation blocks geometry and ditch geometry.

Figure 2. Drainage ditch with an integrated deformation zone – test No. 001 (left) and drainage ditch of classical construction (concrete face) – test No. 002 (right).

of the vehicle nearby the airbag control unit (1000 g) and in the head centre of the gravity of both dummies (500 g). In both tests, airbags were taken out of service, primarily because of the scientific approach to the tests. The aim of the tests was to simulate the worst possible scenario in relation to the measured values. The weight of the vehicle in the test including H III dummy, P6 dummy and the measuring equipment was 1,161 kg.

The vehicle was steered into the ditch by means of the guiding system fixed to the pavement and it impacted frontally the culvert face of the drainage ditch, the slope angle being given by parameters of the ditch (see Figure 3). The whole course of the crash test was being recorded with a high-speed camera (min. 1000 fr·s^{-1} at 1280×1024).

2.3. Assessing criteria

When comparing the two crash tests and quantifying the results, the criteria evaluating the safety of the restraint systems according to EN 1317 as well as the biomechanical criteria evaluating head injuries were used [9–11].

2.3.1. Criterion ASI (Acceleration severity index)

Acceleration Severity Index is a criterion used for assessing road restraint systems according to EN 1317 [12]. The ASI criterion is measured from the measured acceleration on the vehicle body (detector on the tunnel nearby vertical gravity axis projection). It assesses severity range of the pulse affecting the person sitting nearby the measured point of the vehicle. According to EN 1317 the value of ASI should not exceed the value of 1, or if you like of 1.9 for the given impact severity levels A to C, see Table 1.

Impact severity levels			
Level	Maximal tolerated values		
A	ASI $\leq$ 1.0		
B	1.0$\leq$ASI$\leq$1.4	and	THIV$\leq$33 km·h^{-1}
C	1.4$\leq$ASI$\leq$1.9		

Table 1. Assessment of impact severity by means of the ASI criterion.

The criterion can be expressed mathematically as:

$$ASI(t) = \left[(\overline{a}_x/\hat{a}_x)^2 \; (\overline{a}_y/\hat{a}_y)^2 \; (\overline{a}_z/\hat{a}_z)^2 \right]^{1/2}, \quad (1)$$

where $\hat{a}_x$, $\hat{a}_y$ and $\hat{a}_z$ are limit values for particular acceleration components and can be interpreted as a value of applied acceleration during which the risk of a grave injury of the passenger is minimized (max. light injuries). For a fastened passenger the limits are generally used $\hat{a}_x = 12\,g$, $\hat{a}_y = 9\,g$, $\hat{a}_z = 10\,g$. The magnitudes $\overline{a}_x$, $\overline{a}_y$ or if you like $\overline{a}_z$ are filtered components of the acceleration. ASI is set as maximum of the range $ASI(t)$.

FIGURE 3. Testing vehicles and dummies positioning.

2.3.2. Criterion THIV (Theoretical head impact velocity)

The concept of the theoretical head impact velocity (THIV) was developed for assessement of severity index of a vehicle passenger who gets into a collision with the restraint system. The passenger in the vehicle is perceived as a freely moving object (head) that, in compliance with the vehicle changing its speed, when having got into contact with a vehicle restraint system, goes on in its movement until it hits the surface inside of the vehicle. The volume of theoretical head impact velocity is interpreted as a level of crash severity upon the restraint system.

$$THIV = \left[\dot{x}_b^2(t) + \dot{y}_b^2(t)\right]^{1/2}, \qquad (2)$$

where $\dot{x}_b^2(t)$ or if you like $\dot{y}_b^2(t)$ are the coordinates of the theoretical head velocity in relation to the vehicle coordinate system. The detailed calculation together with the implementation of coordinate systems is a subject to a norm.

This criterion is chosen in the case when the vehicle is not peopled by biomechanical dummies. Its limit is set by the EN 1317 norm to 33 km·h^{-1}. It is rounded up to the whole number.

2.3.3. PHD criterion (Post-impact head deceleration)

The PHD criterion used to be an additional criterion of assessing a level of impact severity. Since a revision of the norm (EN 1317) in 2010 this criterion has not been followed. However, it can be used as an information marker when analyzing performed crash tests:

$$PHD = max\left[\ddot{x}_c^2(t) + \ddot{y}_c^2(t)\right]^{1/2}, \qquad (3)$$

where $\ddot{x}_c^2(t)$ or if you like $\ddot{y}_c^2(t)$ is acceleration of the theoretical head after the very first contact with a conceptional structure. The PHD should not exceed the value of 20 g.

2.3.4. HIC criterion (Head injury criterion)

This criterion can be perceived as a measurement of the probability of head injury during an impact. It is calculated as a function maximum of the acceleration resultant $a(t)$.

$$HIC = \left[\frac{1}{t_2 - t_1}\int_{t1}^{t2} a(t)dt\right]^{2.5}(t_2 - t_1), \qquad (4)$$

where $a(t)$ = final acceleration [g], t_1 and t_2 = instants of time in the course of the impact determining beginning and the end of the interval the HIC volume of which is the highest. The length of the interval (t_2ˇt_1) is 36 ms if it did not come into contact with a solid structure. As for the calculation of a maximal value of the impact the time interval of 15 ms (HIC15) is used. The limit value of the criterion HIC is 1000 – the limit indicates approx. 50 % probability of severe head injury occurrence [13, 14].

2.3.5. Criterion 3 ms

Contrary to the previous criterion this one can be applied not only to head injuries. Its limit value assesses toleration for occurrence of severe injuries. The limit value for the head is 80 g. The interpretation of the criterion: the acceleration higher than 80 g cannot operate for a longer period than 3 ms [15].

3. Results

3.1. Test No. 001

The drainage ditch with an integrated deformation zone, a nominal impact speed of 50 km·h^{-1} was complied (the real speed was 47 km·h^{-1}).

Figure 4 demonstrates a course of the test recorded with a high speed camera; the vehicle is due to a deformed structure lifted above the barrier.

In the chart of Figure 5 accelerations measured in three planted places are being recorded. The red curve corresponds with acceleration measured on the body of the vehicle; the green curve presents acceleration of the head of the driver dummy, the blue one shows acceleration for the child passenger. The blue background stands for a time interval when main material deformation of a structure of an integrated

Figure 4. A course of the test No. 001 – the vehicle is due to a deformed structure lifted above the barrier.

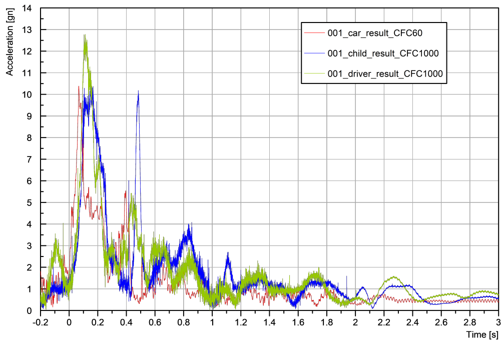

Figure 5. Test No. 001 of drainage with an integrated deformation zone – acceleration time course.

deformation zone was going on (time 0 ms up to approx. 200 ms). From approx. 700 ms the vehicle does not make any forward movement.

Impact phases:

0 ms – first contact with a drainage ditch culvert face,

0-100 ms – main deformation of the drainage ditch structure and of the vehicle deformation zone,

65 ms – interaction of the drainage ditch structure deformation and vehicle deformation zone – the area of an impact of maximal acceleration upon the body of the vehicle,

100-150 ms – the area with maximum measured acceleration affecting the head of the adult dummy, without any contact with an interior of the vehicle, an apex of forward movement of the dummy,

100-170 (or if you like 250) ms – maximum acceleration affecting the head of the child dummy, without any contact with the vehicle interior, the apex of forward movement of the dummy,

100-230 ms – ongoing deformation of the drainage ditch – the vehicle being lifted up due to a distorting structure,

420-470 ms – backward movement of the driver dummy, contact with the head restraint,

Approx. from 430 ms – minimum forward movement, vehicle shifts to a final position,

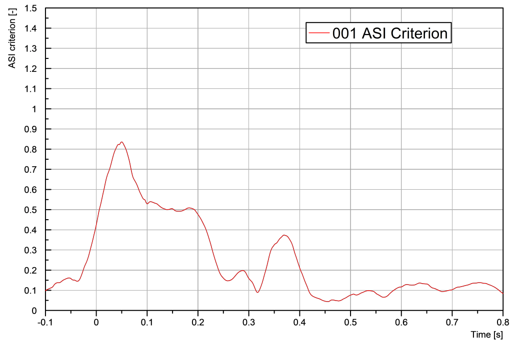

Figure 6. ASI criterion in test No. 001.

480 ms – apex of backward movement of the child dummy and a contact with the head restraint,

530 ms – the vehicle, due to after impact movement, climbed up the distorted structure of the drainage ditch, up to approx. 700 ms. Forward movement is noticeable, succeeded by stabilization and "shifting" to a final position in th ditch,

860 ms – the heads of both dummies crashed the door (window glass) – the windows had been due to a better quality of the camera recording removed before the test (usability of the recording for following point trajectory "tracking").

3.1.1. ASI criterion

The course of this criterion can be found in the graph on Figure 6. The maximal value of ASI was measured in the time of 48.5 ms, being it 0.8 (after rounding), the limit value of 1 was not exceeded. The deformable drainage ditch structure thus fulfils requirements for the level A of the impact severity.

3.1.2. HIC criterion and the criterion of 3ms

HIC Criterion – the driver and child dummy calculated values of the HIC criterion were deep below the set limit value of 1000, see Table 2.

Criterion of 3ms – neither in this case the limit value of 80 g was reached, see Table 2. In compliance with the HIC criterion it can be said that the probability of a serious head injury is nearly zero.

3.1.3. Criteria THIV and PHD

For test No. 001 any calculation of THIV and PHD criteria can be perceived as unnecessary. Since during test No. 002 the data depreciation with the driver dummy occurred, these criteria are chosen as referential in such a way so that the results of both tests could be compared. Neither the THIV, nor PHD criterion exceeded their limit values, see Table 3.

	HIC36			3ms		
Test No. 001	HIC36	T1 [ms]	T2 [ms]	[g]	T1 [ms]	T2 [ms]
Driver	17.6	96.6	132.6	12.0	117.4	120.5
Child	10.9	135.0	171.0	10.1	145.9	149.1

Table 2. Overall chart of HIC and 3ms criteria, test No. 001.

Test No.	ASI		THIV	PHD	
001	[-]	T1 [ms]	[km·h^{-1}]	T1 [ms]	[g]
Value	0.8	48.5	28	147.5	5.0

Table 3. Overall chart of THIV and PHD criteria, test No. 001.

Figure 7. Test No. 002 – drainage ditch of a classical construction.

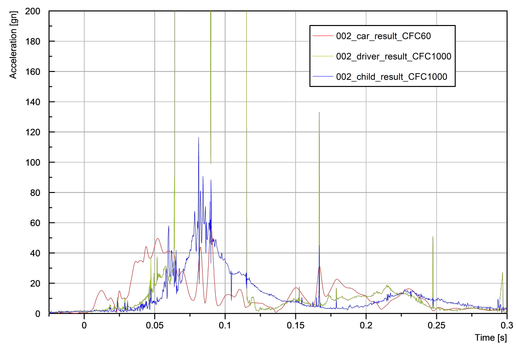

Figure 8. Test No. 002 of drainage ditch of classical construction – acceleration time course.

3.2. Test No. 002

Drainage ditch of a classical construction, nominal impact speed of 50 km·h^{-1} was complied (the real speed was 45 km·h^{-1}).

During test No. 002 crashing into a concrete drainage ditch face (standard construction) a measuring range of the accelerometer was exceeded with the driver dummy (500 g). That is why a measuring sector of approx. 65 ms to 115 ms could not be assessed for this place. The reason for range exceeding was a contact of the dummy with the steering wheel. Note: However, it cannot be stated that within the course of the whole stated time period the acceleration higher than 500 g was affecting the dummy. Most probably it was just the impulse higher than 500 g, which at the same time caused a short time measuring fallout with the measuring channel.

Impact phases:

0 ms – the first contact of the front of the vehicle with a concrete drainage ditch culvert face,

0-22 ms – buffer deformation,

22-70 ms – engine space deformation,

64 ms – the driver dummy – contact of the thorax with the steering wheel, a measuring range of 500 g was exceeded on the accelerometer,

72 ms – the ond of the forward movement – the vehicle bounces from the solid structure,

80 ms – the driver dummy – head contact with the steering wheel,

110 ms – forward movement of both dummies finished, the beginning of the backward movement,

approx. 200 ms – crash of both dummies into the head restraint of the seat – the impact of an eccentric character – in between the head restraint and the side structure of the vehicle,

294 ms – crash of the child dummy into the frame of the side window,

approx. 400 ms – total stabilization of the movement.

3.2.1. ASI criterion

The ASI reached in the time of 33.6 ms a level of 3.1. For comparison, restraint systems with lowest requirements for safety – impact severity level C – must fulfil the ASI value lower than 1.9 (see Table 1).

3.2.2. HIC criterion and the criterion of 3ms

Due to a failure of measuring (see above) the criteria HIC and 3ms for the driver dummy could not be calculated. In order to be able to compare adequately both crash tests despite this failure the Theoretical Head Impact Velocity criterion can be used (THIV) together with an additional PHD (Post-Impact Head

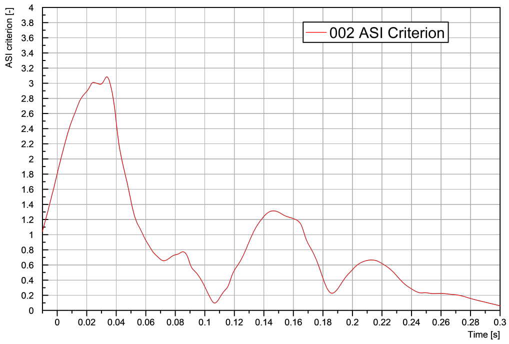

FIGURE 9. ASI criterion in test No. 002.

FIGURE 10. Deformation of drainage ditch with an integrated deformation zone after test No. 001.

Deceleration) criterion that can be calculated when the course of vehicle deceleration is known.

3.2.3. CRITERIA THIV AND PHD

As for the THIV criterion a set limit of 33 km·h^{-1} was exceeded, the value of 51 km·h^{-1} was measured and calculated. The PHD criterion reached value little below the limit of 20 g.

4. DISCUSSION

Due to the deformation of the drainage ditch construction (Figure 10) the duration of the crash event is prolonged – transformation of the kinetic energy it spread into a longer time period – which results in a decrease in affecting powers. Due to the impact with the drainage ditch culvert face equipped with the deformable block the damage of the left front corner of the car body occurred during test No. 001, together with the deformation of a cooler, a shift in the suspension of the left front wheel in the backward direction (see Figure 11).

The deformation of the longitudinal beam did not occur, nor tearing of the engine block, the cockpit remained intact, too, the front left door could be opened without any difficulty.

Due to the impact with the drainage ditch culvert face with concrete face (Figure 12) the engine was torn from the right top hinge during test No. 002 together with cabling, the front face was significantly deformed, see Figure 13; the cooler, hood, bumper stiffener and mounting (hinge) of the left front fender were deformed. The fender got torn from the hinge, also the setting of the left front fender was deformed

FIGURE 11. Vehicle damage after test No. 001 – drainage ditch with an integrated deformation zone impact.

FIGURE 12. Deformation of drainage ditch with an integrated deformation zone after test No. 002.

and a manifold destruction of the intake together with a short circuit occurred. Based on all this information, a model was created for subsequent simulation and use in forensic engineering [16].

Figure 14 shows the mutual comparison of acceleration/deceleration that was measured on the body of the vehicle in the very first 300 ms of the event during both implemented tests. The difference in the course of both events is clearly visible. When carrying out an impact test of the culvert face equipped with deformable blocks, the values of affecting deceleration were five times lower than in the case of the drainage ditch of a standard construction. The significant difference in ASI criterion in both tests is clearly visible in Figure 15.

5. CONCLUSION

The objective of these experiments was to prove that deformable blocks meet the requirements for the restraint function with a calculated deceleration factor and that they cut down a risk of grave and fatal injuries of the vehicle passengers when colliding with the drainage ditch. Impact severity assessed by means of the ASI criterion was in this case 4 times higher than as for the impact into the deformable block. When assessing a biomechanical force, the HPC criterion for the child dummy head and the THIV criterion can be used. In accordance with the calculated HPC values it can be predicted that the child would – in case of an impact with a drainage ditch with a deformable structure under conditions analogical to implemented tests with a probability of more than 99 % – get by without any injury whereas in the case of an impact into a standard drainage ditch, i.e. unfortunately the most widely spread type of a construction, it would suffer in 40 % from injuries of the highest severity AIS 3+ (grave to fatal injury) and only in approx. 2 % it would get by unharmed [17, 18]. According to the THIV

	HIC36			3ms		
Test No. 002	HIC36	T1 [ms]	T2 [ms]	[g]	T1 [ms]	T2 [ms]
Driver	–	–	–	–	–	–
Child	613.6	71.2	102.8	48.6	86.4	89.6

Table 4. Overall chart of HIC and 3ms criteria, test No. 002.

Test No.	ASI		THIV	PHD	
001	[-]	T1 [ms]	[km·h^{-1}]	T1 [ms]	[g]
Value	3.1	33.6	51	113.6	19.2

Table 5. Overall chart of criteria THIV and PHD, test No. 002.

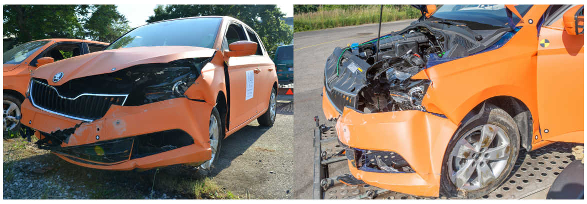

Figure 13. Vehicle damage after test No. 002 – drainage ditch with an integrated deformation zone impact.

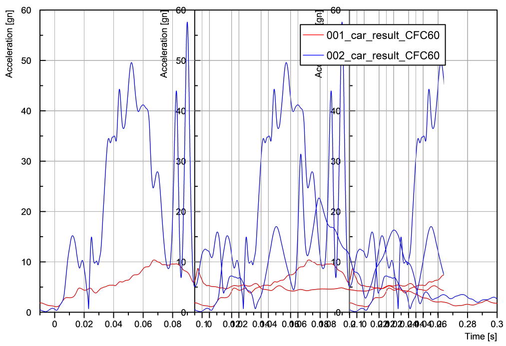

Figure 14. Vehicle acceleration time course – comparison.

criterion, which abstracts from equipping the vehicle with anthropometric devices, the used deformable structure would meet the requirements for road restraint systems according to EN 1317. The functionality of deformable drainage ditch culvert faces has been hereby proved experimentally.

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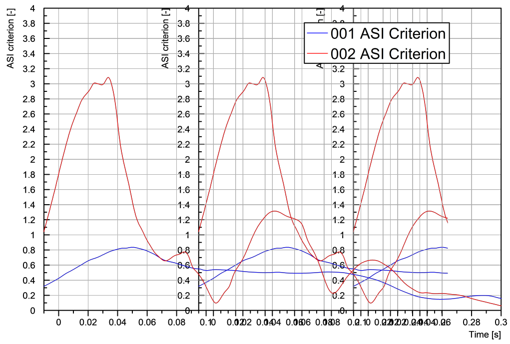

Figure 15. ASI criterion time course – comparison.

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