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NUMERICAL ANALYSIS OF A BRIDGE PIER SUBJECTED TO TRUCK IMPACT

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Abstract: *The paper presents description and comparison of the procedures prescribed by the European standard EN 1991-1-7 for bridge pier impact load. The methods incorporate static and dynamic analysis and are compared with a outcomes from a detailed FEM model of a truck prepared in the AUTODYN software. The outcomes are evaluated and conclusions are drawn.*

Keywords: ***Impact loading, numerical modelling.***

1. Introduction

In some cases of the structural arrangement, the vehicle impact can represent the decisive loading for the design of bridge substructure.

In the present design standards, the Eurocodes, there is a special part dealing with the accidental load caused from impact of road vehicles, trains, vessels etc., EN 1991-1-7. In the most common design cases the less sophisticated method based on an equivalent static load is used in the design praxis. The other method based on dynamic analysis is ignored because it is more demanding and requires performing of a special dynamic analysis.

The two methods provided within this standard are described and compared among each other. Later, the two methods are compared to the outcomes from a detailed FEM model of a truck prepared in the AUTODYN software.

2. Vehicle impact loading according to EN 1991-1-7

The standard EN 1991-1-7 (2007) provides procedures for assessing load from impact of road vehicles, trains, vessels etc.

The load can be obtained by:

- Equivalent static load
- Dynamic analysis

2.1. Equivalent static load

The equivalent static load should provide the same effect as a vehicle impacting the structure. This simplification can be used for:

- Verification of the static equilibrium
- Verification of the structural resistance
- assessing of the deflection caused by the impact

The load is divided according to the part of the structure it influences:

- Impact of the substructure
- Impact of the superstructure

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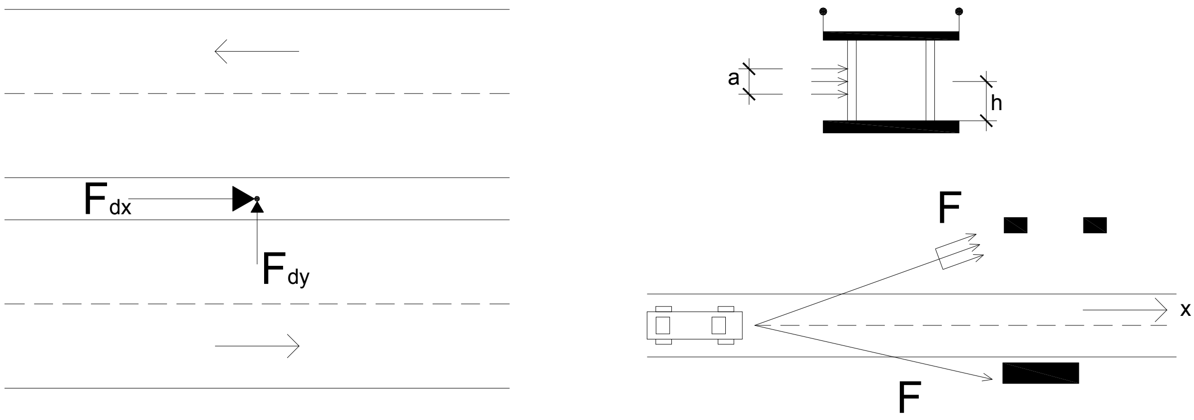

Fig. 1: left: definition of the impact forces; right: vertical alignment of the impact force (according to EN 1991-1-7 (2007))

Table 1: Design values of the impact forces on bridges over road network (according to EN 1991-1-7 (2007))

Category of the communication	**Force Fdx [kN]**	**Force Fdy [kN]**
Motorways and main roads	1000	500
Other roads	750	375
Local roads	500	250

The load to substructure can be taken from *Table 1*, explained in *Fig. 1*. The longitudinal and transverse forces do not act simultaneously.

The impact force acts in the height h (*Fig. 1*) and can be redistributed to an area with the height a. Values of the variables are provided within the cited design standard.

2.2. Dynamic analysis

A more detailed procedure for assessing the impact load is provided in Appendix C of EN 1991-1-7.

The impact bifurcates to soft and hard impact. In the case of the hard impact, the impacting vehicle deflects while the impacted structure remains stiff and unmoved. On the contrary, during the soft impact the impacted structure deflects (e.g. safety barriers). The hard impact can be used in the case of a vehicle impacted bridge pier.

The maximum dynamic force is defined as change of momentum in time:

$$F_0 = \frac{m \cdot v_r}{\Delta t} \tag{1}$$

where v_r is the speed of the impacting vehicle at the time of the impact

m is the mass of the impacting vehicle $m = \rho AL$

Δt is the duration of the impact (force impulse) $\Delta t = \sqrt{m/k}$

k is the equivalent stiffness of the impacting vehicle vztahem $k = EA/L$

E is the modulus of elasticity

A is the cross-sectional area

L is the length of the impacting vehicle

ρ is the volumetric mass of the impacting vehicle.

The impacting force is constant during the impact or increases linearly (*Fig. 2*).

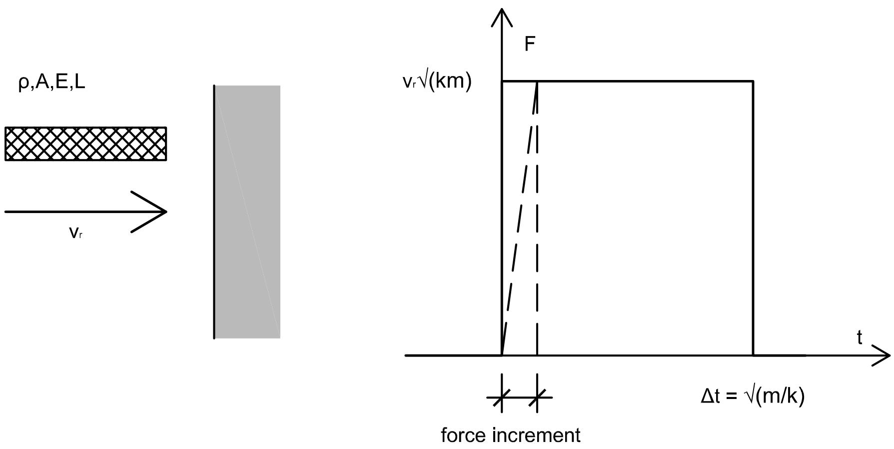

Fig. 2: Model of the impact, F = dynamic interaction force (according to EN 1991-1-7, (2007))

Table. 2: Design values of the mass of the impacting vehicle and the dynamic impact force F0; (according to EN 1991-1-7 (2007))

Category of the communication route	**mass**	**speed**	**deceleration**	**impact force**	**breaking distance**
	m	***v0***	***a***	***F0***	d_b **a)**
	[kg]	**[km/h]**	**[m/s²]**	**[kN]**	**[m]**
Motorway	30 000	90	3	2 400	20
Road in a urban are a)	30 000	50	3	1 300	10

a) speed reduced to 50 km/h

3. The assessment procedure according to EN 1991-1-7

The vehicle impact load is regarded as an accidental loading by the EN 1991-1-7. Therefore an accidental load combination has to be set-up.

In general, an accidental load combination can be analytically described as:

$$E_d = E\{G_{k,j}; P; A_d; (\psi_{1,1} or \psi_{2,1}) Q_{k,1}; \psi_{2,i} Q_{k,i}\} \quad j \geq 1; i > 1 \tag{2}$$

where the combination in the brackets {} can be written as:

$$\sum_{j\geq 1} G_{k,j} \text{"+"} P \text{"+"} A_d \text{"+"} (\psi_{1,1} or \psi_{2,1}) Q_{k,1} \text{"+"} \sum_{i>1} \psi_{2,i} Q_{k,i} \tag{3}$$

where the choice of the combination values $\psi_{1,1}$ or $\psi_{2,1}$ lies on the particular accidental design load. The combination can contain the design accidental load (impact, fire, etc.) or is related to the sesign situation following the accidental loading where $A = 0$.

4. Numerical modelling

This part of the paper is focused on application of the procedures described in the previous paragraphs. The utilization of the equivalent static force and the use of the dynamic analysis is compared to a 3D FEM model of a struck impacting a bridge pier.

4.1. Description of the bridge the impact loads are applied on

The impact loads are applied on a typical prestressed concrete two span bridge (see *Fig. 3* and *Fig. 4*). The superstructure is connected to a frame pier which is located in the median of a motorway. This bridge was built in 2005 by the joint venture of the companies STRABAG and SMP Construction as a part of the D3 motorway in south from Prague in the Czech Republic. Both the substructure and the superstructure are made of concrete C30/37. The span lengths are 25,750 and 21,735m. The middle pier is assessed to vehicle impact, the effect of the safety barriers is neglected.

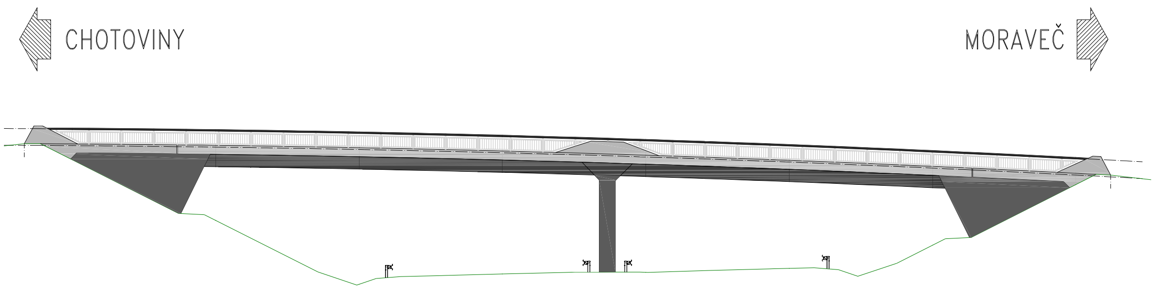

Fig. 3: View of the assessed bridge near Chotoviny

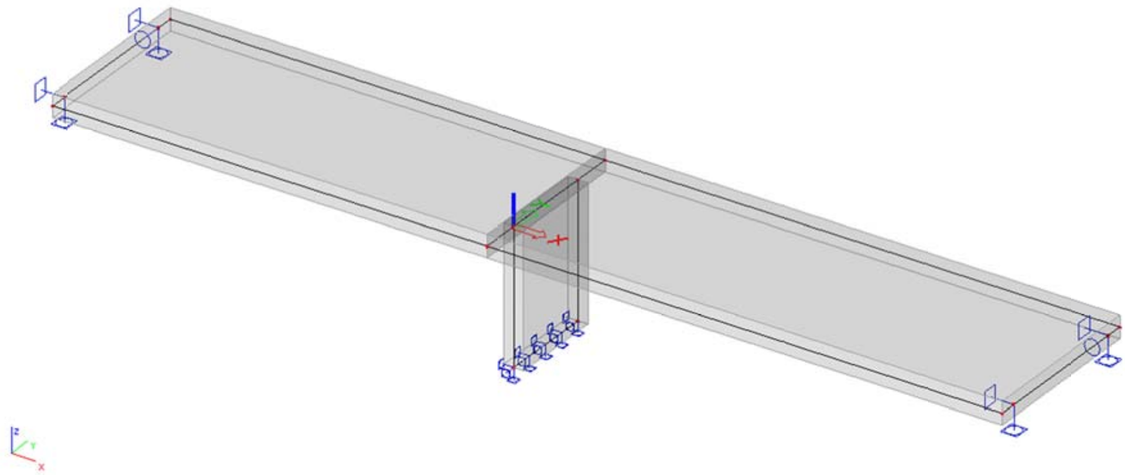

Fig. 4: Schematic slab FEM model of the bridge near Chotoviny.

4.2. Application of the equivalent static force

When using the equivalent static force for assessing a bridge pier subjected to impact load (EN 1991-1-7, (2007)), the impact forces are applied according to *Table 1*. The forces are placed in the most adverse position (*Fig. 5*), but do not act simultaneously. The impact forces are distributed on the centre-line of the slab which is modelling the bridge pier (*Fig. 6*). The distributed load acts from 0,5 to 1,5m above the crossed motorway.

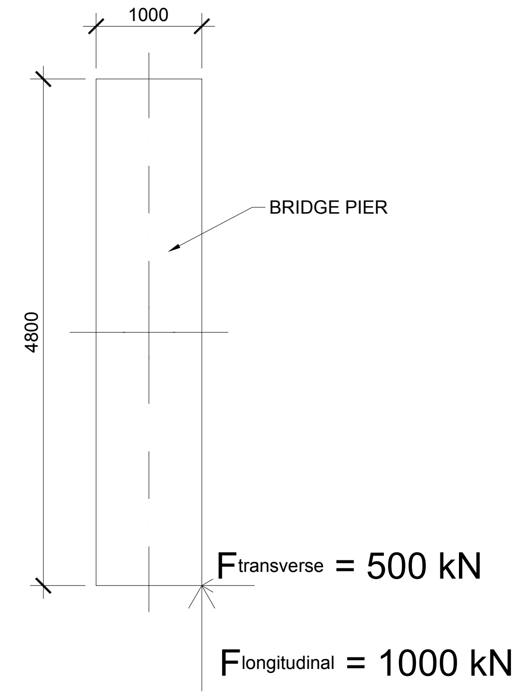

Fig. 5: Location of the impact forces

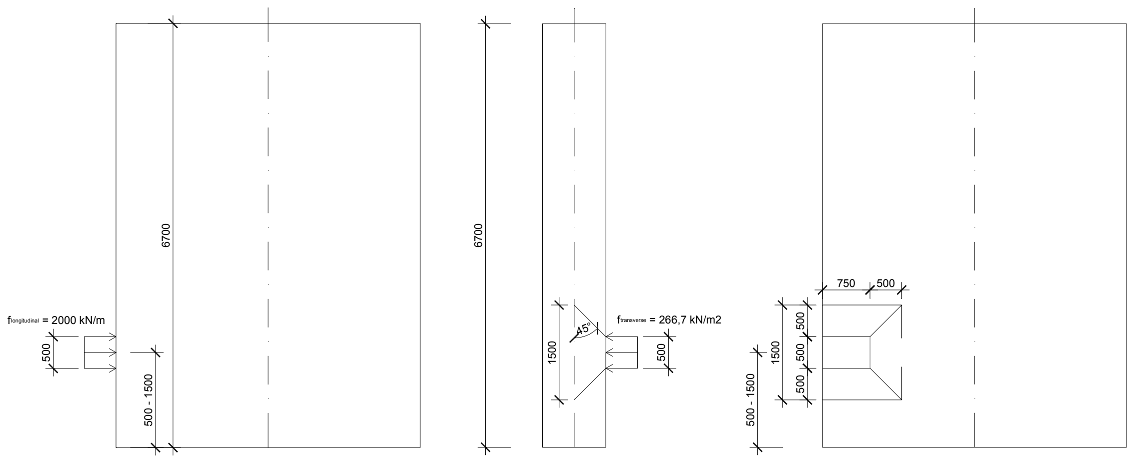

Fig. 6: Areal distribution of the impact forces on the bridge pier centre-line

The effect of the equivalent impact load on the bridge pier is assessed by a linear FEM analysis. The accidental load combination according to EN 1990 (2007) (see Eq. 6 and 7) is used for combining the effects of self weight, dead load and traffic load (LM1 according to EN 1991-2 (2005)) if it acts adversely.

The shear combined with the effect of torsion is the decisive load case, utilization of the cross-section is 60%, see *Table 3*.

Tab. 3: Summary of truck impact modelled with the use of the equivalent static force

	Impact direction	Decisive loading	Maximal impact force	Utilization	Dynamic coefficient
Truck impact	longitudinal	shear	1000,00 kN	60%	×
	transverse	shear	500,00 kN	60%	×

4.3. Dynamic analysis

When using the Appendix C for assessing a bridge pier subjected to impact load (EN 1991-1-7, (2007)). The impact force acts under the angle of 10° (*Fig. 7* and *Table 2*) from the horizontal axis of the motorway; for simplification, the impact angle is taken 0° and the force acts in the direction of the traffic on the motorway.

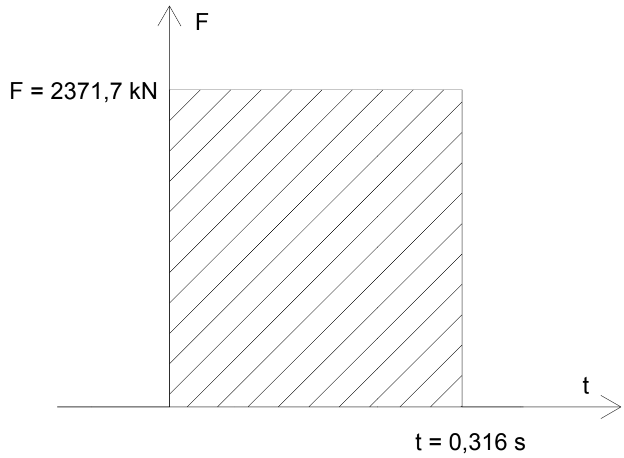

Fig. 7: Time distribution of the impact force for the dynamic analysis

In the following step, the dynamic system with two degrees of freedom is set up (*Fig. 8*).

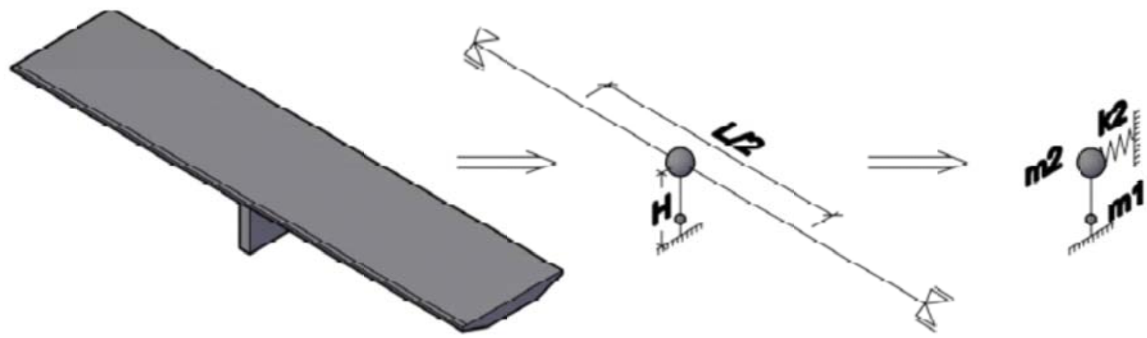

Fig. 8: Setting up the dynamic system of the bridge pier subjected to truck impact

The bridge pier is modelled by a cantilever which is supported by as spring on its free end. The stiffness of the spring *k2* corresponds to the lateral bending stiffness of the superstructure supported at bridge bearings. The mass *m2* is taken as the mass of the upper half of the bridge pier and the middle part of the superstructure (self weight + dead load) as can be seen in *Fig. 9*. The mass *m1* is taken as the mass of the lower part of the bridge pier and is located in the spot of the vehicle impact (1,5m above the motorway). In the next step, the matrix of docility and the matrix of damping of the dynamic system is prepared (Rayleighs damping, damping coefficient taken 7% for reinforced concrete). In this case, the matrix of mass is

$$M = \begin{bmatrix} 40{,}2 & 0 \\ 0 & 670{,}7 \end{bmatrix} \cdot 10^3 \text{ kg},$$

the matrix of docility is

$$\delta = \begin{bmatrix} 0{,}026917 & 0{,}021283 \\ 0{,}021283 & 0{,}186188 \end{bmatrix} \text{ mm}$$

and the matrix is

$$C = \begin{bmatrix} 32213{,}00 & -3653{,}47 \\ -3653{,}47 & 8820{,}28 \end{bmatrix} \cdot 10^3 \text{ kg/s}.$$

From the known input values, the dynamic response of the system is obtained with the use of direct integration of the equation of motion (Fig. 9).

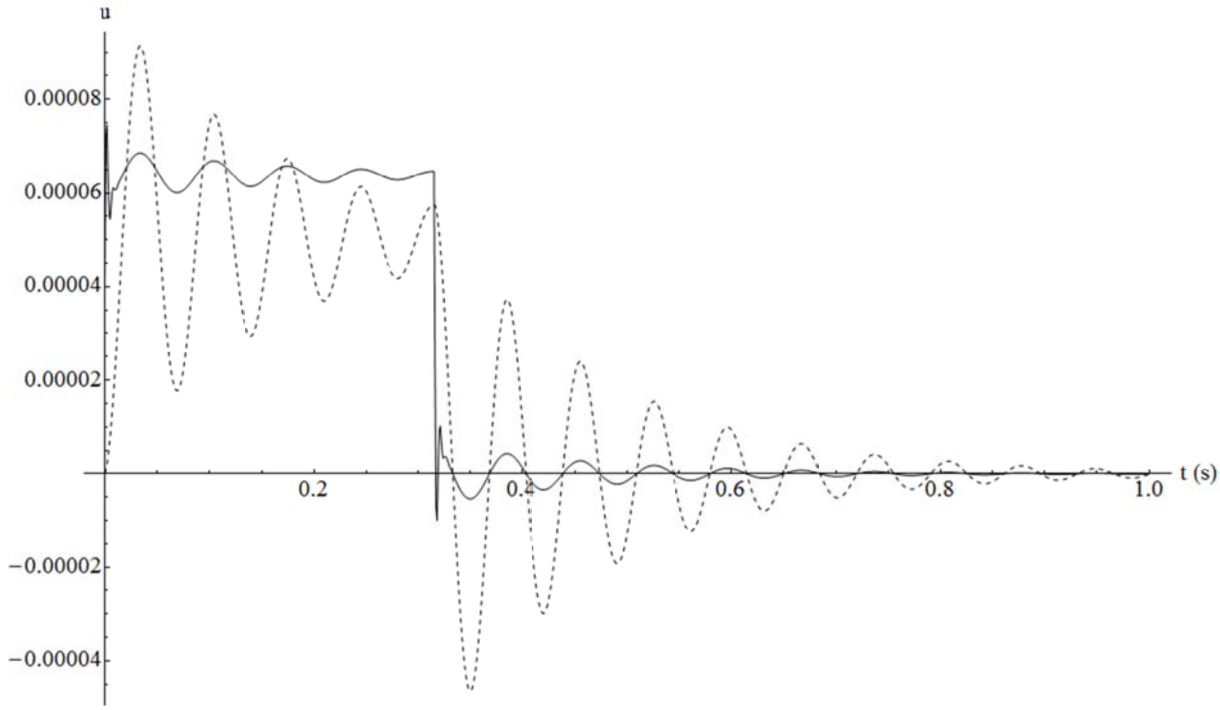

Fig. 9: Dynamic response of the system to the impact load, - - deflection at the top of the bridge pier, — deflection at the spot of the impact

The force couple causing the maximal deflection is determined reversely from the matrix of docility (3038,82;-337,28) [kN]. The 2D model of the bridge pier is then loaded by these forces and the resultant internal forces are determined.

The initial impact force in the direction of the traffic is 2371,7 kN, but the force causing the maximum deflections is 3038,82 kN; the resulting dynamic coefficient is 1,3).

The shear is the decisive load case, utilization of the cross-section is 80%, see *Table 4*.

Tab. 4: Summary of truck impact modelled with the use of the dynamic analysis

	Impact direction	Decisive loading	Maximal impact force	Utilization	Dynamic coefficient
Truck impact	longitudinal	shear	3038,82 kN	80%	1,3
	transverse	×	×	×	×

4.4. Nonlinear numerical analysis

Unlike both of the procedures for assessing a bridge pier subjected to vehicle impact incorporated in the EN 1991-1-7 which (based on simplifying assumptions) provide impact loading for the structure, the method described in this part aims to model a real truck hitting a bridge pier in full scale and then obtain the impact load reversely. The truck impact model is prepared in the ANSYS AUTODYN software.

The truck IVECO Trakker ADN140T50 (*Fig. 10 and 11*) was taken as the hitting vehicle. The 3D computational model was prepared in the RHINOCEROS 4.0 software using 2D and 3D finite elements which represent the decisive structural parts of the vehicle.

Fig. 10: The truck IVECO Trakker ADN140T50

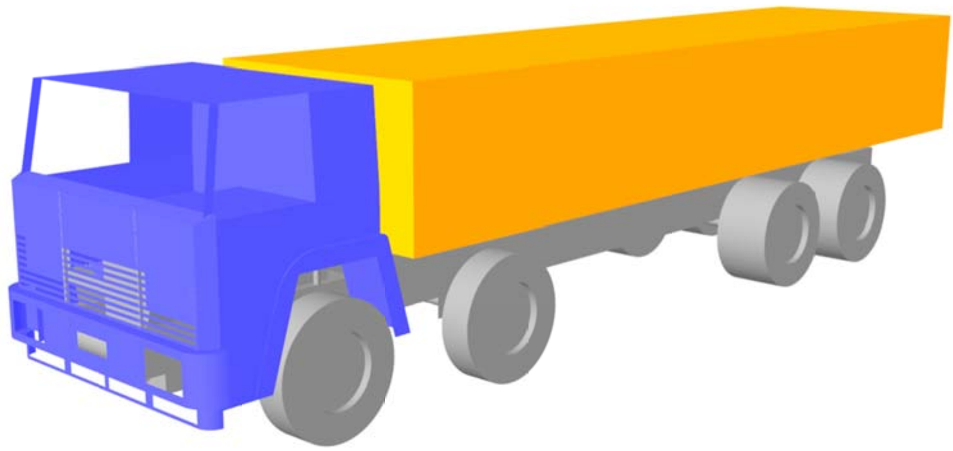

Fig. 11: Computational model of the truck

The FE-modell is composed of a main frame carrying the motor (*Fig. 12*), a cab with the bumper (*Fig. 13*) and the load of the truck (for achieving the maximum allowable load). The main frame is composed of two horizontal U-profiles (309,0 x 80,0 x 10,0 mm), the motor block (3D brick element) and supplemental elements (thickness 10mm) which are connecting the cab. The cab (including the housing) is modelled by 2mm thick 2D elements; the bumper is modelled by 5mm thick 2D elements. The truck load is modelled by a steel block with reduced mass for obtaining the desired total weight 32 tonnes.

The material model used for the truck is linear steel without damage (material model with damage would increase the computing time, which is already now at approximately 96hrs). The finite elements which reach the limit deformation are eroded (i.e. dismissed from the model), but their mass and velocity stay within the system. This approach is satisfactory since the goal of the truck FE model is only to transmit the load to the bridge pier, not to perform a “crash-test study” of the truck.

The geometrical model is meshed using the Lagrange’s network with an element size of 50mm.

The vehicle is moved with a speed of 90km/h towards the bridge pier.

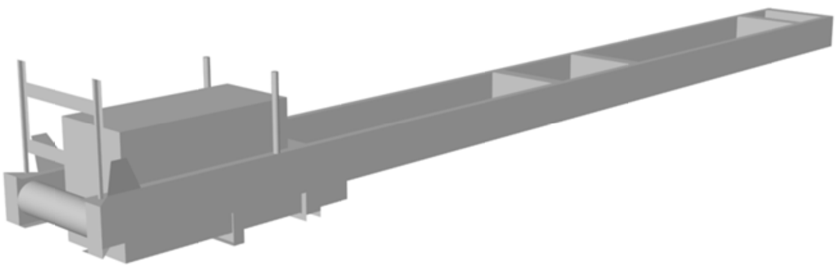

Fig. 12: Computational model of the main frame carrying the motor

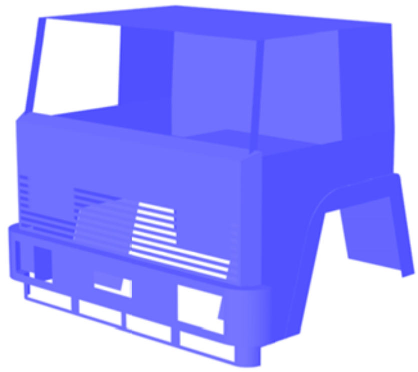

Fig. 13: Computational model of the cab including the bumper

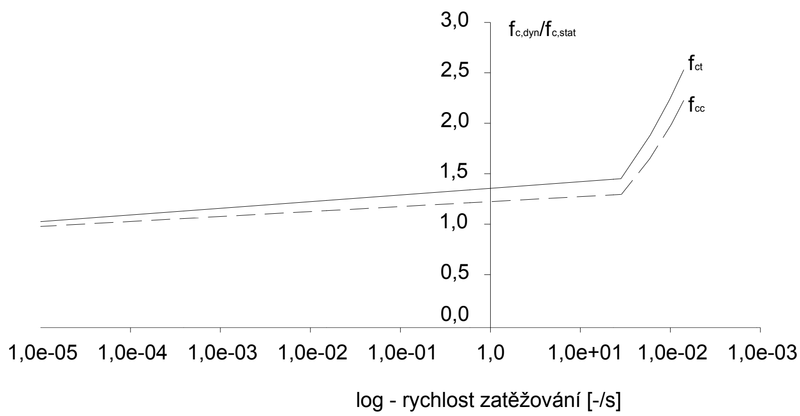

Fig. 14 Increase of the strength (both tensile and compressive) depending on the speed of loading (according to CEB-FIP Model Code 1990 (1993))

The material of the bridge pier was chosen to illustrate its behaviour when subjected to blast; the two main aspects are:

- Damage of the material when subjected to ultimate loading

- Increase of the strength (both tensile and compressive) depending on the speed of loading (dynamic increase factor)

The material model RHT for brittle materials with damage was chosen for concrete. This model incorporates the strain-rate effect, which describes the increase of strength with the speed of loading (*Fig. 14*).

The concrete bridge pier is modelled without reinforcement; the concrete strength class was taken C30/37. The effect of the safety barriers is neglected, the 32 tonne vehicle hits the pier in the direction of the traffic in the speed of 90km/h (*Fig. 15*).

The elements of the pier erode when reaching 100% damage. The elements of the vehicle erode when reaching the ultimate deformation; the erosion increases the energetic instability of the system with the use of Lagrange's network, which sets boundaries to the used element size.

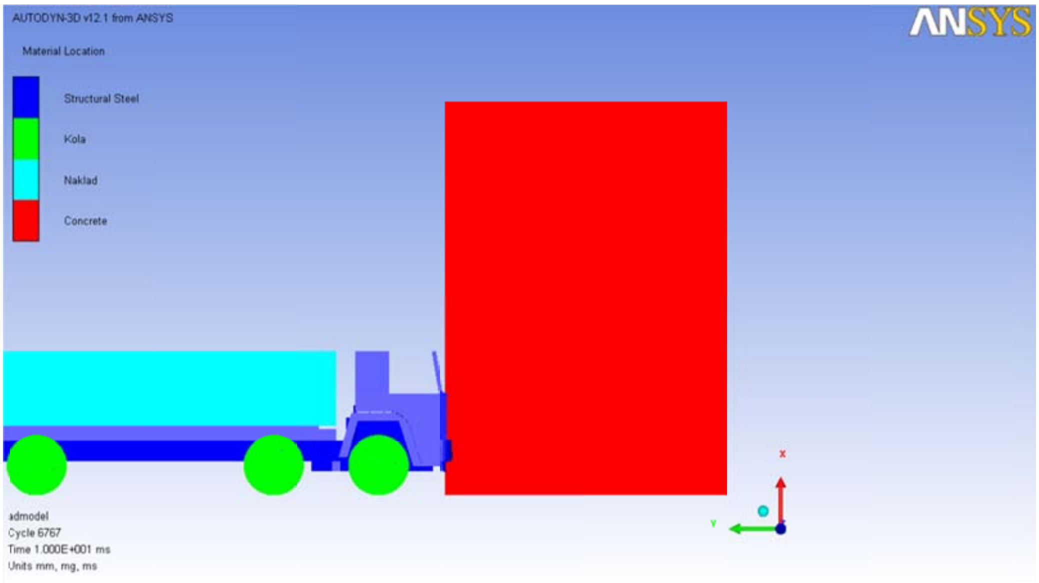

Fig. 15: The 32 tonne truck hitting the bridge pier.

The truck speed in at the moment of the impact together with the speed of the vehicle during the impact was taken from the FE model (Fig. 16). The total duration of the impact was 334ms.

The acting impact force was obtained from the change of the momentum using Eg. 1 (*Fig. 17*), the unlikely local extremes were neglected. The maximum impact force is 5762,65 kN (9707,76 kN local extreme).

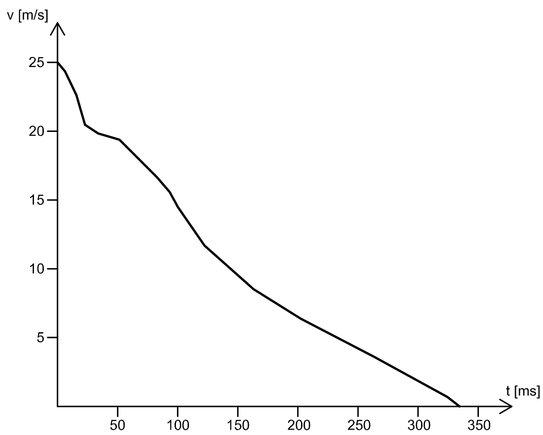

Fig. 16: Speed of the vehicle during the impact

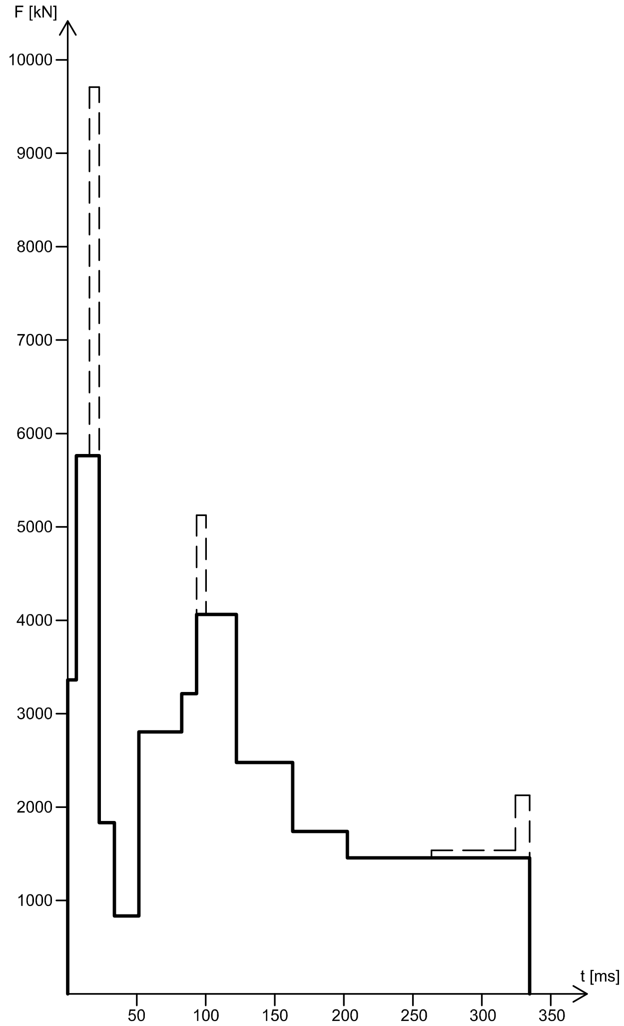

Fig. 17: The acting impact force during the impact, - - real time dependence, — the time dependence used in the assessment

With the known course of the impact force the same procedure as in the previous part is used.

From the known input values, the dynamic response of the system is obtained with the use of direct integration of the equation of motion. The force couple causing the maximal deflection is determined reversely from the matrix of docility (6471,64;-580,75) [kN] (*Fig. 18*). The 2D model of the bridge pier is then loaded by these forces and the resultant internal forces are determined.

The initial impact force in the direction of the traffic is 5762,65kN (9707,76 kN local extreme), but the force causing the maximum deflections is 6471,64 kN (10802,05 kN local extreme); the resulting dynamic coefficient is 1,12).

As in the previous chapter, shear is the decisive load case, utilization of the cross-section is 170% (280% for the local extreme), see *Table 5*.

Tab. 5: Summary of truck impact modelled with the use of a real vehicle

	Impact direction	**Decisive loading**	**Maximal impact force**	**Utilizati on**	**Dynamic coefficient**
Truck impact	longitudinal	shear	6471,64 kN	170%	1,12
	transverse	×	×	×	×

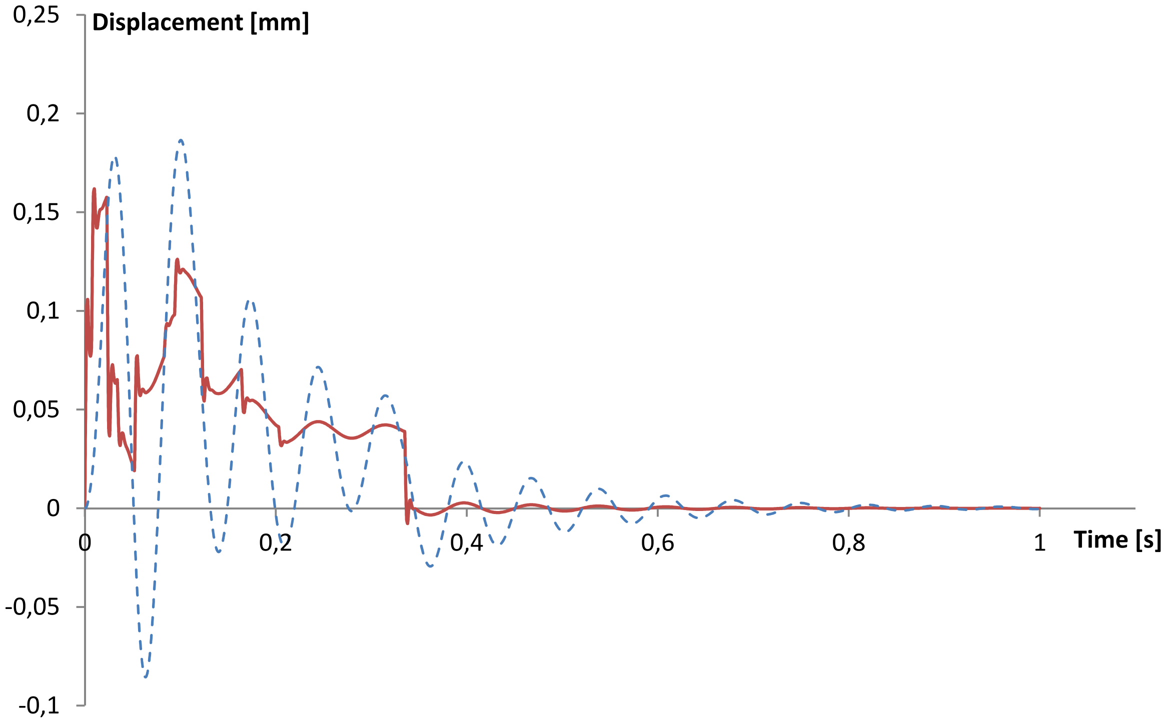

Fig. 18: Dynamic response of the system to the real truck impact load, - - deflection at the top of the bridge pier, — deflection at the spot of the impact

5. Conclusions

Three different approaches to vehicle impact were assessed. The first two are incorporated in the EN 1991-1-7 design code: the equivalent static load and the dynamic analysis. The pier of the modelled bridge provided satisfactory resistance to the impact loading. The commonly used method, the equivalent static load provided smaller loading and utilization than the load provided by the dynamic analysis. The equivalent static force was three times smaller than the impact force obtained by the dynamic analysis.

The third tested approach lied in full-scale modelling of the impacting truck. A non-linear computational model of a 32 tonne truck impacting the concrete pier was prepared. From the speed of the vehicle during the impact, the acting impact force during the 334 ms long impact was calculated. This force is two times higher than the impact force obtained by the dynamic analysis and six times higher than the equivalent static force. Thusly the resistance of the bridge pier is not satisfactory when using regular standard approaches for its assessment.

It is questionable whether to use the force calculated from the full-scale modelling of the impacting truck for the assessment of the bridge pier cross-section according to present design standards. The bridge pier experienced some cracking and erosion of crushed concrete elements. By the opinion of the authors, the damaged pier should be loaded by the design load and its residual bearing capacity verified by the means of a non-linear analysis. This analysis will be performed in the ongoing research.

Acknowledgement

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References

ČSN EN 1991-1-7 (2007) *Zatížení konstrukcí, Obecná zatížení – Mimořádná zatížení*. ÚNMZ.
ČSN EN 1990 (2007) *Zásady navrhování konstrukcí*. ÚNMZ.
ČSN EN 1991-2 (2005) *Zatížení konstrukcí, Zatížení mostů dopravou*. ÚNMZ.
CEB-FIP (1993) *Model Code 1990* Comité Euro-International du Béton.