Design of structures for accidental design situations

J. Marková, K. Jung
Czech Technical University in Prague,Klokner Institute, Czech Republic

ABSTRACT: The probabilistic methods are applied for the assessment of theoretical models of accidental impact forces due to road vehicles recommended in EN 1991-1-7. The lower bound of the design impact forces recommended in Eurocodes for different categories of roads seems to be rather low. It is shown that the upper bound of impact forces should be rather applied for the design of structures located in the vicinity of roads provided that no other safety measures are provided.

1 INTRODUCTION

EN 1991-1-7 (2006) gives provisions for the determination of accidental actions on structures caused by gas or dust explosions or impacts due to various types of traffic means as heavy cars, trains, forklift trucks, ships and helicopters. Different strategies can be accepted taking into account whether the sources of accidental actions may be expected (impacts, gas explosions) or hardly identified only, e.g. human gross errors.

When the source of extreme action is identified, the structural members should be designed for the theoretical value of accidental action, or the measures for load reduction should be provided (e.g. road safety barriers). Where the potential hazard is difficult to be identified, the recommended procedures for limiting an extent of localised failure in buildings are given in Annex A of EN 1991-1-7 (2006) including general provisions for structural robustness.

For the specification of accidental actions, the probabilistic methods of the theory of structural reliability and methods for risk assessment may be applied. In some cases the representative value of accidental action may be selected in such a way that there is a probability less than $p = 10^{-4}$ per year for a structure that the selected or a higher impact force will occur. Commonly the nominal values are applied for the design or verification of structures against the effects of accidental actions.

The value of accidental action should be taken into account in the design of structure with respect to the potential consequences of structural failure, the probability of exceptional event occurrence, the measures accepted for prevention or mitigation of potential hazards, the exposition of structure and the level of acceptable risk. It is not considered in Eurocodes that the structure would resist to all extreme actions and some residual risk should be commonly accepted. The residual risk concerns all accidental actions with a low probability of occurrence, not assumed in the project, as well as actions that are known and considered but for which certain small risks should be accepted.

The annual maximal accepted probability of structural failure based on limiting individual risk may be expressed according to ISO 2394 (1998) as

$$p_{\mathrm{f}} < 10^{-6}/\mathrm{p}(d/f) \qquad (1)$$

where p(d/f) is the probability of casualties given a structural failure. The annual maximal probability of structural failure based on limiting the risk with respect to human lives may be expressed as

$$p_{\mathrm{f}} < A\,N^{-k} \qquad (2)$$

where N is the expected number of fatalities per year. For the constants A and k, the values $A = 0{,}01$ to 0,1 and $k = 1$ to 2 are recommended in ISO 2394 (1998). In case that for a specific structure the maximum accepted value $N = 5$ is specified on the basis of risk analysis, it may be determined from condition (2) that annual maximal accepted failure probability for a structure should be less than $p_{\mathrm{f},1} < 4\times10^{-4}$ (for fifty years design working life $p_{\mathrm{f},50} < 2\times10^{-2}$). The reliability index $\beta_{\mathrm{t},1} = 3{,}35$ per one year and $\beta_{\mathrm{t},50} = 2{,}05$ per fifty years corresponds to these probabilities. It should be noted here that Eurocodes do not give recommendations for the target reliability level in accidental design situations.

The structures are classified according to EN 1991-1-7 (2006) to three classes considering the possible consequence of failure.

- Class CC1 (low consequences): no special requirements are needed with respect to accidental actions except to ensure that the basic rules for robustness and stability are met.
- Class CC2 (medium consequences): a simplified analysis by static equivalent action models may be adopted or prescriptive design/detailing rules applied.
- Class CC3 (high consequences): examination of the specific case should be carried out to determine the level of reliability and the depth of structural analyses (risk assessment, non-linear or dynamic analysis).

For the design of structures (mainly in Class CC2), the design values of accidental forces are commonly represented by equivalent static forces.

The alternative procedures given in EN 1991-1-7 (2006) for specification of impact forces due to road vehicles that may be applied for the verification of static equilibrium or load-bearing structural capacity are analysed in the following text.

2 MODELS OF IMPACT FORCES

National standards as well as international prescriptive documents give in many cases different models of impact forces due to heavy road vehicles (their total weight is greater than 3,5 tons). For example, the Czech national standards recommend the impact force 1000 kN for motorways without considering the distance of the structure to the road. In comparison, the British standards recommend accidental design forces about five time greater than Czech standards which should be taken into account for a structure located in a distance less than 4,5 m from the road. During the development of EN 1991-1-7 (2006) the values of impact forces introduced in the preliminary standard ENV 1991-2-7 (1998) were increased on the basis of national comments of CEN Member States up to the value 2500 kN taking into account individual road categories.

The indicative values of impact forces due to impact of heavy road vehicles recommended in the final draft of EN 1991-1-7 (2006), which may be modified as Nationally Determined Parameters (NDP), are given in Table 1. These forces represent an indicative (minimum) design requirement that might be exceeded.

The final acceptance of the lower bound in Eurocodes was also caused due to the fact that for some countries it was rather difficult to keep the originally proposed range of impact forces for the different categories of roads (e.g. for motorways 1000 to 2500 kN) as they might be obliged due to their legislation to accept more strict upper bound.

Table 1. Indicative horizontal static equivalent design forces.

Category of roads	Force $F_{d,x}$ [kN]	Force $F_{d,y}$ [kN]
Motorways and main roads	1000	500
Country roads (v > 60 km/h)	750	375
Urban areas	500	250
Courtyards	150	75

The minimum values introduced in Table 1 were also accepted in the Czech National annex and only the categories of roads were slightly modified according to the national tradition in construction.

Eurocode EN 1991-1-7 (2006) gives information how to consider the effects of different slope of the terrain and location of the structure. The resulting impact forces F_d versus increasing distance d of the structural member for the vehicle velocity of 90 km/h are indicated in Fig. 1. A flat terrain is considered for impact force F_0, downhill for force F_1 and uphill terrain for F_2, based on the assumptions given in Annex C.

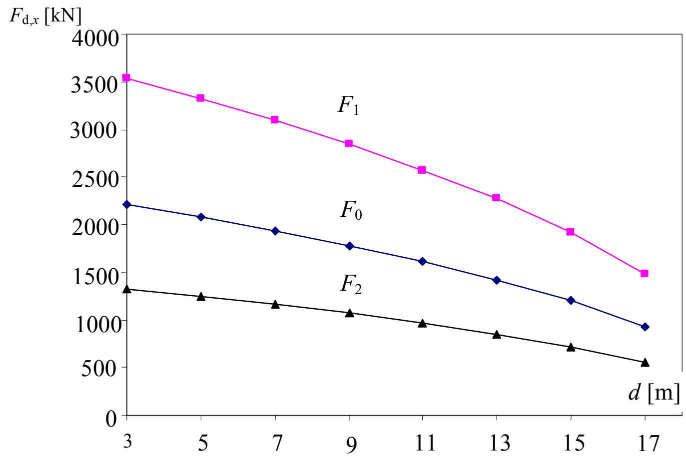

Figure 1 The impact force F_d versus distance d of a structural member, for v_0 = 90 km/h and three types of terrain (F_0 for flat terrain, F_1 downhill, F_2 uphill).

.

The possibility to define the force as a function of the distance from the axis of the nearest traffic lane to the structural member was not used in the Czech National annex as the relevant roughness of the terrain depends on many circumstances (season of the year, weather conditions, vegetation). The forces $F_{d,x}$ (direction of normal travel) and $F_{d,y}$ (perpendicular to the direction of travel) are not needed to be considered simultaneously during the design of structure for accidental impact.

3 ANALYSIS OF IMPACT FORCES

Eurocode EN 1991-1-7 (2006), Annex C gives alternative procedures for the specification of impact forces due to road vehicles. The maximum resulting interaction force under the assumption of the linear deformation of the car is given as

$$F_0 = \sqrt{v_0^2 - 2as}\,\sqrt{k\,m} \qquad (3)$$

where v_0 is the vehicle velocity at the moment of road leaving, a is the average deceleration, s is the distance from the point where the heavy vehicle leaves the traffic lane to the structural member, k is the equivalent elastic stiffness of the vehicle and m is its mass. The design forces F_d due to vehicle impact can be assessed as

$$F_d = F_0\,\sqrt{1 - \frac{s}{s_{br}}} \qquad (4)$$

where s_{br} is the braking distance, $s_{br} = v_0^2/(2a\sin\alpha)$ where α is the angle between the traffic lane and the course of impacting vehicle. Recommended values of the vehicle mass m, velocity v_0, deceleration a, collision force F_0 and braking distance as given in EN 1991-1-7 (2006) are shown in Table 2.

Table 2. Design values for mass, velocity and collision force.

Category of roads	Velocity v_0 [km/h]	Collision force F_0 [kN]	Breaking distance s_{br} [m]
Motorways	90	2400	20
Country roads *	70	1900	20
Urban areas	50	1300	10

* According to the Czech National annex.

If these recommended values are inserted to exp. (3) and (4), the upper bound of impact forces may be determined. The resulting forces for relevant categories of roads considering three different distances s are given in Table 3.

Table 3. Design values of impact force F_d [kN] for distance d.

Category of roads	$d = 3$	$d = 6$	$d = 9$ [m]
Motorways	2400	2300	2270
Country roads	1800	1750	1700
Urban areas	1250	1200	1150

4 PROBABILISTIC ASSESSMENT

The probabilistic methods of the theory of structural reliability are applied for the determination of impact forces. Two alternative procedures given in EN 1991-1-7 (2006), Annexes B and C, are analysed.

1. The probability of a structural member being impacted by a heavy vehicle leaving its traffic lane may be assumed to be 0,01 per year. The recommended failure probability for a structural member, given a heavy vehicle in its direction, is $10^{-4}/10^{-2} = 0{,}01$, ENV 1991-2-7 (1998). The accidental design force F_d may be specified on the basis of the following condition

$$P\left(\sqrt{mk\left(v^2 - 2as\right)}\right) \geq F_d = 0{,}01 \qquad (5)$$

where all probabilistic models of basic variables may be based on the recommendations of Eurocodes and documents of JCSS [5]. The values of accidental impact forces are analysed and given for the three considered distances d in Table 4.

Table 4. Design values of impact force F_d [kN] (approach 1).

Category of roads	$d = 3$	$d = 6$	$d = 9$ [m]
Motorways	2910	2850	2810
Country roads	2300	2250	2190
Urban areas	1580	1500	1430

2. The design impact force may be determined on the basis of the following condition of Annex B

$$P_f = n\,T\,\lambda\,\Delta x\,\mathrm{P}[\sqrt{km(v^2 - 2as)} > F_d] \qquad (6)$$

where n is a number of vehicles per time unit, T the period of time under consideration, λ is a probability of a vehicle leaving the road per unit length, Δx is a part of the road from where the collision may be expected, other variables are introduced above. The variable Δx may be determined as

$$\Delta x = \frac{b}{\sin\mu(\alpha)} \qquad (7)$$

where the variable b depends on the structural dimension. For structural members such as columns a minimum value of b follows from the width of the vehicle (b = 2,5 m may be considered). The angle α of a collision is assumed to be 10°C (Rayleigh distribution). The resulting impact forces taking into account exp. (6) are given in Table 5.

Table 5. Design values of impact force F_d [kN] (approach 2).

Category of roads	$d = 3$	$d = 6$	$d = 9$ [m]
Motorways	2950	2880	2800
Country roads	2310	2260	2200
Urban areas	1900	1800	1740

Figure 2 indicates where should be selected the design impact forces F_d for the recommended value of reliability index β_t (about 2,3) corresponding to the probability 0,01 in exp. (5).

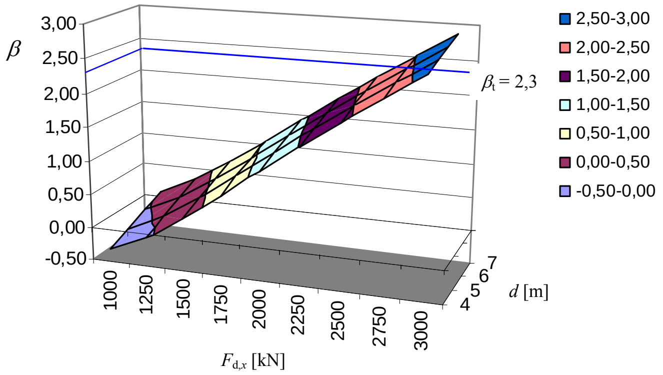

Figure 2 Design impact force $F_{d,x}$ versus distance d for recommended index β for roadways (probability of failure 10^{-2}).

The resulting impact forces determined on the basis of alternative probabilistic procedures are considerably greater than the minimum (indicative) requirement for impact forces given in Eurocodes (see Table 1). For motorways, the impact forces are in a range from 2,9 to 2,8 MN, for country roads the forces are in a range from 2,3 to 2,2 MN, for roads in urban areas, the impact forces are in a broader range from 1,9 to 1,4 MN (depending on the applied probabilistic approach) for three study cases of distances d from 3 to 9 m.

Presented study indicates that for the design of structural members located nearby the traffic routes the upper bound of the accidental impact forces should be rather recommended in the National annex to EN 1991-1-7 (2006) provided that no other safety measures are accepted.

5 RELIABILITY ANALYSIS OF BRIDGE PIER

The reliability of reinforced concrete column designed according to EN 1992-1-1 (2004) as a supporting member of a bridge on the highway D8 in the North-West part of Bohemia is analyzed, Report (1998). For the persistent design situation, the fundamental design combination according to the twin of expressions (6.10a,b) is given in EN 1990 (2002) as

$$\sum_{j\geq 1}\gamma_{G,j}G_{k,j}\ "+"\ \sum_{i>1}\gamma_{Q,i}\ \psi_{0,i}Q_{k,i} \tag{8}$$

$$\sum_{j\geq 1}\xi\gamma_{G,j}G_{k,j}\ "+"\ \gamma_{Q,1}Q_{k,1}\ "+"\ \sum_{i>1}\gamma_{Q,i}\ \psi_{0,i}Q_{k,i} \tag{9}$$

where G_k and Q_k are the characteristic values of permanent and variable actions, γ_G and γ_Q the partial factors for permanent and variable actions, ψ_0 the combination factor for accompanying actions and ξ the reduction factor for permanent actions.

The combination of actions for accidental design situation may be determined on the basis of expression (6.11) of EN 1990 (2002) given as

$$\sum_{j\geq 1}G_{k,j}\ "+"\ A_d\ "+"\ \psi_{1,1}Q_{k,1}"+"\sum_{i>1}\ \psi_{2,i}Q_{k,i} \tag{10}$$

where ψ_1 and ψ_2 are the coefficients for the frequent and quasi-static values of variable actions. It is assumed that the column is loaded by the self-weight of the superstructure G_1 = 1607 kN, permanent action G_2 = 775 kN, and self-weight of the column G_3. The column is loaded by the group of loads gr1a according to EN 1991-2 (2003) which consists of the double-axle concentrated loads (tandem system TS) Q_1 = 235 kN, uniformly distributed load (UDL system) Q_2 = 280 kN and uniformly distributed loads on footways Q_3 = 119 kN (adjustment factors are included). The lower bound of impact forces is considered according to Eurocodes as indicated in Table 1.

For the design of reinforced concrete column (dimensions 0,80 × 0,80 m), the concrete Class C 25/30 and reinforcement S 500 (f_{ck} = 25 MPa, f_{yk} = 500 MPa) are used. The partial factors for concrete and steel γ_c = 1,5, γ_s = 1,15 are considered. For the design of reinforcement, EN 1992-1-1 (2005) is applied.

For the determination of internal forces and reinforcement, the software RFEM (Modul Columns) was applied. The theoretical area of reinforcement A_s for persistent and accidental design situation is introduced in Table 5 and also applied in the probabilistic reliability analysis.

The reliability of the column is verified on the basis of the probabilistic methods of the theory of reliability. The limit state function may be expressed as the difference between the random bending resistance moment M_R and effects of external forces M_E given as

$$g(\xi_R\, M_R,\ \xi_E\, M_E) = \xi_R\, M_R - \xi_E\, M_E \tag{11}$$

where the probabilistic models of all basic variables applied in analysis are introduced in Table 6. It is assumed that some of the variables are deterministic, others are random with normal (N), lognormal (LN), gama (GAM) and gumbel distribution (GUM). The statistical properties are described by means and standard deviations based on the previous own studies and also recommendations of the research organisation JCSS [8].

Table 5. Design area A_s of reinforcement and reliability index.

Combination	Area of reinforcement $A_s \times 10^4$ [m^2]	Index β
1. Exp. (6.10a,b)	12,8	5,87
2. Exp. (6.11), 1000 kN	101,25 (98,39)	2,05
3. Exp. (6.11), 750 kN	69,73 (67,38)	1,94
4. Exp. (6.11), 500 kN	38,58 (36,81)	2,03

The resulting values of the reliability index β determined from the reliability analysis by the method FORM and software Comrel (2003) are given in the last column of Table 5.

Table 6. Probabilistic models of basic variables.

Basic variable	Sym.	Distr.	Units	μ	σ
Material properties	f_c	LN	MPa	35	5
	f_y	LN	MPa	560	30
	E_s	DET	GPa	200	0
Cross-sectional geometry	b	N	m	nom.	0,01
	h	N	m	nom.	0,01
	d_1	GAM	m	nom.	0,005
Reinforcement	A_s	DET	m^2	nom.	0
Model uncertainties	ξ_R	N	-	1,1	0,11
	ξ_E	N	-	1,0	0,10
Concrete density	γ_c	N	MN/m^3	0,025	25×10^{-4}
Models for actions	Q_1	GUM	MN	nom.	0,3 μ
	Q_2	GAM	MN/m^2	nom.	0,1 μ
	Q_3	GAM	MN/m^2	nom.	0,1 μ
	A	LN	MN	nom.	0,4 μ

The reinforced concrete column designed for the persistent design situation only has greater reliability index (β = 5,87) than is the target reliability β_t = 3,8 according to EN 1990 (2002) for the common class of structures CC2.

The reliability index of the column designed also for the accidental design situation according to Eurocodes seems to be in a range from 1,9 to 2,05. If the condition given in expression (2) based on ISO 2394 (1998) is considered then the reliability of the column designed for the accidental action seems to be sufficient. However, in case that the recommendations given in ENV 1991-2-7 (1998) is considered, then the upper bound of impact forces should be applied in the design of the column.

6 CONCLUDING REMARKS

The new European standard EN 1991-1-7 provides for various road categories only indicative lower bound of impact forces due to the heavy road vehicles that is accepted in the Czech National annex.

The probabilistic analysis of alternative procedures recommended for determination of design impact forces due to road vehicles indicates that the specified impact forces (for roadways and speedways up to 2,95 MN, for urban areas up to 2,3 MN and for local roads up to 1,9 MN) are located near the upper bound of the range of impact forces as it was recommended in the working drafts of EN 1991-1-7.

In case that the dynamic analysis or risk assessment are not provided and no effective provisions are accepted then it should be considered whether it is sufficient to design the structure of class CC2 located near road for the lower bound of impact forces only.

The lower bound of accidental impact forces recommended in Eurocodes seems to represent the minimum requirement which without the application of effective safety measures may lead in case of accidental impact of a heavy vehicle to the undesired failure or collapse of the structural member.

Acknowledgement. This study is part of the project GAČR No.103/06/1521"Reliability and risks of structures in extreme conditions".

REFERENCES

EN 1991-1-7. 2006. Basis of structural design, CEN.
ISO 2394. 1998. General principles on reliability for structures, ISO.
EN 1990. 2006. Basis of structural design, CEN.
ISO 2394. 1998. General principles on reliability for structures
Report RSD - D8/0804 - SO 221 Road flyover III/2473 Hostenice – Brozany, 1998
EN 1992-1-1. 2006. Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings, CEN
EN 1991-2. 2003. Actions on structures – Traffic loads on bridges, CEN.
ENV 1991-2-7.1998. Eurocode 1: Basis of design and actions on structures – Part 2-7: Actions on structures – Accidental actions due to impact and explosions
Holicky M., Markova J. 2005. Basis of the theory of structural reliability and risk assessment, CTU.
Holicky M., Markova J. 2005. Reliability of a concrete column exposed to accidental action due to impact, pp. 556-564, Conference Dundee, UK
JCSS *Probabilistic Model Code*. 2001. www.jcss.ethz.ch
COMREL 8.0. 2003. Structural Reliability System. RCP Consulting software, Germany