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DETERMINATION OF VEHICLE IMPACT LOADS ACCORDING TO DIFFERENT DESIGN CODES

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ABSTRACT

Building structures are designed to withstand various unforeseen impacts and loads – impact, explosion, derailment, etc. The design must limit the possibility of structural failure due to an unknown cause. Shock impacts are characterized depending on the intensity and duration of the impact. Therefore, the elements of the structure can demonstrate different behavior and failures under different concentrated external impacts, including local failures or those on the whole structure.

Depending on local legislation, different structural design codes apply. This paper explores the difference between the design codes for the impact loads. A comparative analysis is made at high speed on the road, as well as at low speed when parking.

1. Introduction

The occurrence of accidental loads of significant value can lead to severe consequences unless special measures are taken. Impact loads are those that can arise from human action. Impact loads are not a consequence of normal use and are not desired. Considerable efforts are made to avoid the impact, for example barriers are put in place. As a result, the probability of an impact occurring is small, while the consequences can be severe.

The basic principle is that the maximum resultant dynamic interaction force is proportional to the velocity at the moment of the impact. In its entirety, the design code

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procedures include many other conditions, the most important of which are: mass of the colliding object, distance to the structure, deceleration, vehicle stiffness, etc. The velocity depends mainly on the location area of the moving vehicle: highway, urban area, courtyard or garage.

Eurocodes [1] are mandatory for the specification of European public works. According to Art. 127 of the Bulgarian regulation [2], when calculating building structures and the effects on them, reference is made to the Eurocode. Yet, many countries outside the European Union do update their National Standards for structural design of building and infrastructures, based on Eurocodes [1, 3].

Design results vary even in countries using Eurocode. Differences are due to the specificities inherent in National Annexes. Among the specified features, different permissible speeds, different normative masses of the vehicles, etc. can be indicated.

2. Eurocode – Dynamic impact design, according to BDS EN 1991-1-7 [1], Annex C

According to the procedure written in [1], impact is an event of interaction between moving objects and construction, in which the kinetic energy of the object is suddenly transformed into deformation energy. In order to determine the dynamic interaction forces, it is a necessity for the mechanical characteristics on the object and the structure to be known. Equivalent static forces are usually used in the designing process.

Nowadays, structural design for impact forces may include some of the following aspects – dynamic effects and nonlinear material behavior.

Criteria for classification of impacts are given in Appendix C of [1]. An impact can be characterized as hard or soft. A definition of high impact is used if the energy is dissipated mainly by the impacting body. The soft impact definition is used if the structure is designed to deform in order to absorb the energy of the impact.

2.1. Eurocode – Hard impact

According to the definition of “hard impact” in Eurocode, the structure is assumed as rigid and fixed, and the hitting object deforms linearly during the impact. The maximum resulting dynamic interaction force is obtained as follows:

$$F = v_r \sqrt{k m}, \quad (1)$$

where v_r is the object velocity at impact; k is the equivalent elastic stiffness of the object, which represents the ratio between the force and total deformation; m is mass of the colliding object. The force from the impact can be presented as a rectangular pulse on the surface of the structure.

$$F \Delta t = m v. \quad (2)$$

In this case the pulse duration is:

$$\Delta t = \sqrt{m / k}. \quad (3)$$

When the colliding object is modelled as an equivalent impacting object of uniform cross-section the used equations are:

$$k = EA / L, \quad (4)$$

$$m = \rho AL, \quad (5)$$

where L is the length of the impacting object; A is the cross-section area; E is the modulus of elasticity; ρ is the mass density of the impacting object.

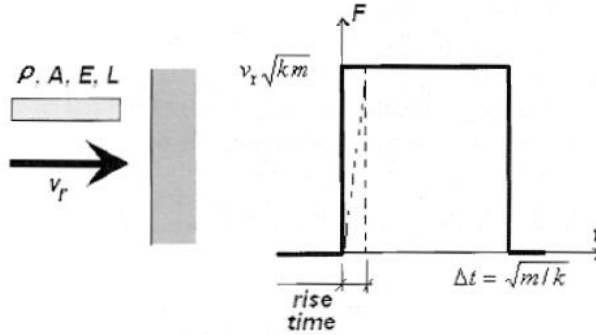


Figure 1. Impact model, F – dynamic interaction force, [1]

2.2. Eurocode – Soft impact

Eurocode defines “soft impact” where the structure is considered as elastic and the colliding object as rigid. In this case, the equations given for the hard impact can be applied, and it can be used k value to be equal to the stiffness of the structure.

If the structure is designed to absorb the impact energy by plastic deformations, provision should be made so that its ductility is sufficient to absorb the total kinetic energy $\frac{1}{2}mV_r^2$ of the colliding object.

In the limit case of rigid-plastic response of the structure, the above requirement is satisfied by the condition of expression:

$$\frac{1}{2}mV_r^2 \leq F_0 y_0, \quad (6)$$

where F_0 is the plastic strength of the structure, i.e. the limit value of the static force F ; y_0 – is its deformation capacity, i.e. the displacement of the point of impact that the structure can undergo.

2.3. Eurocode – impact from aberrant road vehicles

In case of a truck (lorry) impacting a structural element, the velocity of impact is calculated by a set formula taking into account the following factors (with their mean values):

- vehicle velocity;
- average deceleration of the vehicle after leaving the trafficked lane (design value for all cases is 3 m/s²);
- vehicle mass;

- vehicle stiffness (mean value 300 kN/m);
- angle between the trafficked lane and the course of impacting vehicle;
- the braking distance, the value of which changes depending on whether the slope is uphill or downhill.

It is expressly stated that the derived forces are intended to be used with an elasto-plastic dynamic structural analysis. The design values (in Table C.2 of [1] – vehicle velocity, deceleration, mass, etc.) correspond approximately to the average plus or minus standard deviation, given in Table C.1 of [1]. Different values may be chosen, depending on the target safety, the traffic intensity and accident frequency. In addition, a dynamic impact force may be modified on the basis of a risk analysis taking into account the potential consequence of the impact. In absence of a dynamic analysis, the dynamic amplification factor for the elastic response may be assumed to be equal to 1,40 [1].

3. German standards

According to code [4] (for Accidental actions), there are different types of impacts caused by vehicles, depending on the type of street or location where the impact occurs and, in some cases, differentiates between variety of masses and speeds of the impacting vehicle. For car parks (parking lots), the static force depends on the mass of the vehicle for which they are intended. For vehicles with a mass below 2,50 t, the equivalent static load in the direction of the road is 40 kN, while for vehicles with a greater mass, this load is 100 kN.

4. British standards

The first UK national standard for highway bridge loading was introduced by the Ministry of Transport in 1922 [5]. This comprised a standard loading train of vehicles, with a 50 per cent allowance for impact [6]. A brief overview of the development of British norms in dynamic effects is provided in [5]. Summary includes introducing a loading curve for bridges, reduction of impact allowance (because of improvements being made in vehicle suspension systems). In 1954, the impact allowance was reduced (again) to 25 per cent. Greater attention is paid to dynamic effects under normal exploitation. Common to all of these models is that the difference between the effects of moving and stationary vehicles are referred to as ‘impact’ effects and the impact allowances were selected deterministically to represent a typically large effect that would apply to all bridges.

Concern is expressed in [5] that it may become more common for procurement authorities to specify performance criteria rather than to specify the means of meeting those criteria.

According to [7], in the design of bridge superstructures, bearings, substructures, retaining walls and wing walls, the following nominal impact loads shall be applied at the top of the traffic face of high level of containment parapets only:

- a single horizontal transverse load of 500 kN;
- a single horizontal longitudinal load of 100 kN;
- a single vertical load of 175 kN.

The loads should be applied uniformly over a length of 3 meters measured along the line of parapet. According to [7]:

- the vehicle collision loads on bridge supports and structures over highways shall be in accordance with the requirements of the relevant authority;
- the vehicle collision loads on foot/cycle track bridge supports and superstructures over highways shall be in accordance with the requirements of the relevant authority.

On the front page [8] it is written that the European Standard has the status of a British Standard. Its clause 4.7.2.1 (Collision forces on piers and other supporting members) states that for stiff piers the following minimum values are recommended:

- impact force: 1000 kN in the direction of vehicle travel or 500 kN perpendicular to that direction;
- height above the level of adjacent ground surface: 1,25 m.

A part of the British Standard gives dead and minimum recommended imposed loads for use in designing buildings. According to [9], for vehicle barriers for car parks is considered.

The horizontal force F (in kN), normal to and uniformly distributed over any length of 1,50 meters of a barrier for a car park, required to withstand the impact of a vehicle is given by:

$$F = \frac{0,5mv^2}{\delta_c + \delta_b}, \quad (7)$$

where m is the gross mass of the vehicle, in kg; v – is the velocity of the vehicle, normal to the barrier (in m/s); δ_c – is the deformation of the vehicle (in mm); δ_b – is the deflection of the barrier (in mm).

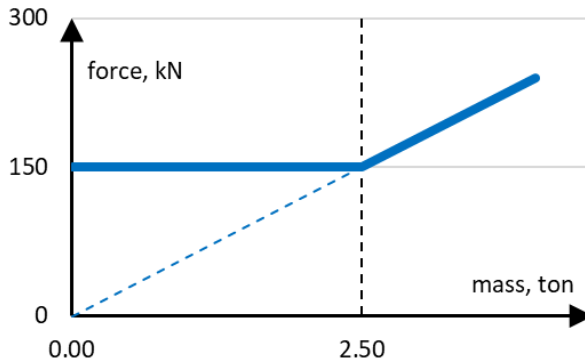


Figure 2. Colliding force vs vehicle mass in tons according to [9]

In cases where the car park has been designed on the basis that the gross mass of the vehicles using it will not exceed 2500 kg, the following values are used to determine the force F : $m = 1500$ kg; $v = 4,50$ m/s; $\delta_c = 100$ mm unless better evidence is available.

For a rigid barrier, for which δ_b may be taken as zero, the force F appropriate for vehicles up to 2500 kg gross mass is taken as 150 kN, see Fig. 2.

If the car park has been designed for vehicles whose gross mass exceeds 2500 kg, the following values are used to determine the force F : m = the actual mass of the vehicle for which the car park is designed, in kg; $v = 4,5$ m/s; $\delta_c = 100$ mm, unless better evidence is available.

5. Spanish standards

According to [10], “Loading for Buildings”, paragraph 4.3.2, the requirements given in this document correspond to those in Eurocode. The following significant difference is observed when calculating the static impact force in a parking lot: while the Eurocode limits the maximum speed of the vehicle to determine the type of road and the equivalent static load, the Spanish Norms limit the maximum mass of the vehicle for which the respective parking lot is designed [11]. In the same study [11], a basic case of an impact caused by a vehicle with a mass of 3000 kg at a speed of 20 km/h in the direction of the road on a building structure located in a parking lot is considered. In this case the dynamic interaction force $F = 167$ kN, by including the stiffness value $k = 300$ kN/m according to [1].

6. American Society of Civil Engineers (ASCE) Standard

ASCE Standard 7-10 [12] provides requirements for general structural design and includes means for determining dead, live, soil, flood, wind, snow, rain, atmospheric ice, and earthquake loads, and their combinations that are suitable for inclusion in building codes and other documents.

According to “Minimum design loads for building and other structures”, [12 and 13], vehicle barrier systems for passenger vehicles should be designed to resist a concentrated load of 26,7 kN.

According to [14], piers or other guideway support elements which are situated on less than 3 m from the edge of an adjacent street or highway should be designed to withstand a horizontal force of 1000 kN.

7. AASHTO Load and Resistance Factor Design (LRFD)

AASHTO LRFD Bridge Design Specifications [15] is the general governing design code for bridges and other highway structures in the United States. According to its paragraph 3.6.5.2 “Vehicle and Railway Collision with Structures” [15], unless specified protection, abutments and piers shall be designed for an equivalent static force of 400 kip (about 1780 kN), which is assumed to act in any direction in a horizontal plane, at a distance of 4 ft (about 120 cm) above ground. The equivalent static force of 400 kip is based on the information from full-scale crash tests of barriers for redirecting 80 kip tractor trailers and from analysis of other truck collisions. The 400 kip train collision load is based on physically unverified analytical work [16], see Fig. 3. For individual column shafts, the 400 kip load should be considered a point load.

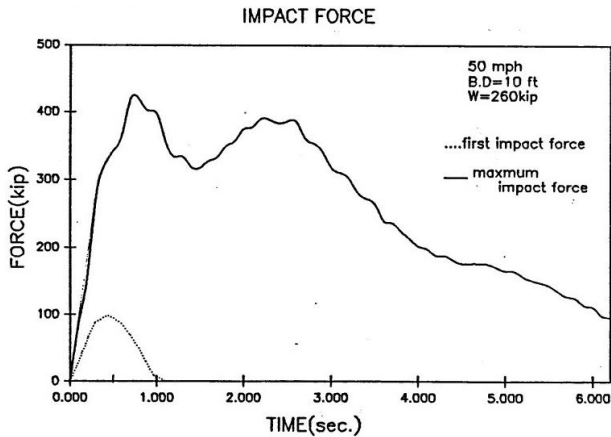


Figure 3. Impact model for cars according to [16]

According to [17], piers of “heavy construction” and crash walls adjacent to railroad tracks shall be designed for a minimum railway collision load of 600 kips (about 2670 kN), applied at an angle up to 15 degrees from the tangent to the railway, see Fig. 4.

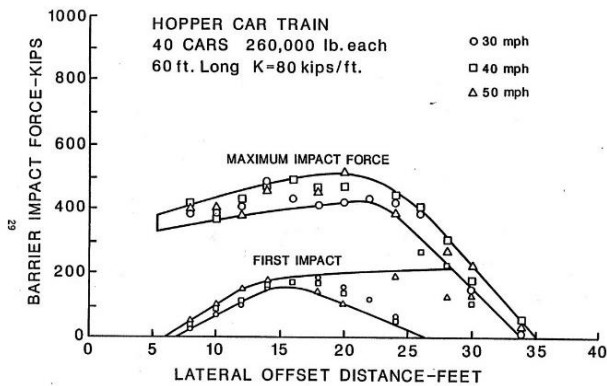


Figure 4. Impact model for trains according to [16]

8. Canadian standards

This topic is covered in paragraph “C3.15 Vehicle collision load“ of [18] and recommendations are given. To prevent collapse, highway bridge piers near the edge of the road surface must be designed to withstand the maximum dynamic force due to such collisions. If the distance between the edge of the road and the pier is 10 meters or more, the probability of a severe collision is considered to be negligible.

Pedestrian bridge piers should be protected by vehicular barriers and need not be designed for the specified collision load. Their consequences of collapse could be minimized during critical periods. The numerical value of the specified collision load is based on the loads used in the German Standard DIN 1072 (1972). It was verified by considering the load and performance factors and maximum lateral impact force due to a 450 kN vehicle.

9. Indian standards

According to [19], in road traffic the requirement that the structure shall be able to resist collision may be assumed to be fulfilled if it is demonstrated that the structural element is able to stop a fictitious vehicle. It is assumed that the vehicle strikes the structural element at a height of 1,20 m in any possible direction and at a speed of 10 m/s (36 km/h).

The fictitious vehicle shall be considered to consist of two masses m_1 and m_2 which during compression of the vehicle produce an impact force increasing uniformly from zero, corresponding to the rigidities k_1 and k_2 . It is assumed that the mass m_1 is broken completely before the breaking of mass m_2 begins.

The following values should be used:

$m_1 = 400$ kg, $k_1 = 10\,000$ kN/m the vehicle is compressed.

$m_2 = 12\,000$ kg, $k_2 = 300$ kN/m the vehicle is compressed.

The described fictitious collision corresponds in the case of a non-elastic structural element to a maximum force of 630 kN for the mass m_1 and 600 kN for the mass m_2 irrespective of the elasticity. It will, therefore, be on the safe side to assume the static force to be 630 kN.

In addition, the breaking of the mass m_1 will result in an impact wave, the effect of which will depend to a great extent on the kind of the structural element concerned. Consequently, it will not always be sufficient to be designed for the static force.

10. Conclusion

The main and expected conclusion is that there is a relatively large inconsistency in the results obtained from different codes. In the Eurocode, a clear definition of impact is given, and the value of the vehicle stiffness is fixed there at 300 kN/m. The same value is used in the [19], but in a more complicated two-vehicle model. The British design code [9] in general refers to [1]. In most design codes norms, the design is based on the relationship (1), but in some of them, a fixed value of the collision force is simply determined depending on the vehicle type (i.e. for trucks – 1780 kN).

The values obtained according to the Spanish norms do not vary depending on the mass and speed of the car, but these parameters are essential in the definition of impact [11]. Unfortunately, it is impossible to predict how high speed can be developed in parking lots, and in fact, in such cases, the risk of a collision is higher.

In different countries, different values are set for high speeds, not only in parking lots, but also on roads, near constructions and bridges. Predictions of the standard in some sections are not very conservative [20] and, therefore, its application could result in damage of the structure.

Design standards have so far paid little attention to the complexity of the problem, while modern engineering increasingly takes into account all incidental loads, as well as natural and man-made disasters – hazards and their impact on buildings and the environment [21]. Considering that impact loads cannot be predicted with certainty, their effects on structures should be minimized by appropriate design and construction.

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ОПРЕДЕЛЯНЕ НА УДАРНОТО НАТОВАРВАНЕ, ПРИЧИНЕНО ОТ ПРЕВОЗНИ СРЕДСТВА СЪГЛАСНО РАЗЛИЧНИ НОРМИ ЗА ПРОЕКТИРАНЕ

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Ключови думи: удар, динамика, импулс, ударно натоварване, скорост превозно средство, норми за проектиране

РЕЗЮМЕ

Строителните конструкции са проектирани да издържат на различни непредвидени въздействия и натоварвания – удар, експлозия, дерайлиране и др. Проектът трябва да ограничава възможността за разрушаване на конструкцията поради неизвестна причина. Ударните въздействия се характеризират с три вида в зависимост от интензитета и продължителността на въздействието. Следователно елементите на конструкцията могат да демонстрират различно поведение и откази при различни концентрирани външни въздействия, включително локални повреди или такива на цялата конструкция.

В зависимост от местното законодателство се прилагат различни норми за проектиране на конструкции. Тази статия изследва различията между проектните норми по отношение на ударните натоварвания. Направен е сравнителен анализ при висока скорост на пътя, както и при ниска скорост при паркиране.

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