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Barrier Loads for Parking Garages

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1.0 Historical Background[1]

In the early 17th century, when old cannons were no longer useful, they were used as bollards for aiding ships to moor alongside quaysides. The cannon was buried in the ground, muzzled first, up to two-thirds of their length, which would leave the rear end protruding above the ground which allowed ropes to be attached. Fig 1 gives a typical description of what they would have looked like.

Fig 1: Plaza de la Catedral, Cuba[2]

The next development would be at the start of the 18th century, where wooden posts were used to manage traffic. One example is the "two oak posts" erected next to the medieval Eleanor Cross at Waltham Cross in Hertfordshire, England in 1772. This was at the expense of the Society of Antiquaries of London, which were installed to stop the Waltham Cross from being damaged by passing carriages.

Due to the transitioning from horses to motorized vehicles, the timber bollards were changed to cast iron. Today, bollards are made out of a variety of materials to meet any requirements they might have.

2.0 Failures of Vehicle Barriers[3]

Many failures of vehicle barriers in parking structures have occurred because of inadequate detailing of reinforcement in the joints and connections. These failures offer tragic examples of vehicles that plunged several stories into the street, with occupants inside. Fig 2 shows a cast-in-place concrete barrier wall failure and subsequent car plunge. In this case, the edge of the concrete slab serves as the base of the wall, and the barrier is a wall-slab system. Test results have shown that concrete wall-slab barrier systems do not meet the IBC's minimum threshold.

Fig 2: Parking Structure in City of Los Angeles, Calif.[3]

Fig 2 shows the barrier-wall system failed at the joint between the vertical wall and the horizontal slab, without any visible damage to the wall as a result of the car impact. This showed that the wall-slab joint is the weakest link in the barrier system. Over the years, studies done by the ACI and the ASCE have shown that the joint is inherently weak in transferring the bending moment and shear force from one member to the other, and experimental work is needed to verify the efficiency of such joints.

3.0 Types of Barriers[4]

There are three principal types of edge restraint:

(i) those that span between primary structural members (commonly horizontally between columns),
(ii) those that cantilever up from the car park deck, and
(iii) those that are monolithic with the deck.

The choice depends upon many factors, such as type of structural frame, deck construction, space available, and required ease of replacement.

The first type consists of cold-rolled, or for longer spans hot-rolled, steel sections that absorb the vehicle energy by yield mechanisms. Recently, wire systems have also been proposed. Fiber composite systems that absorb energy by fracture mechanisms are also potentially suitable to span between structural frame.

The second type consists of cold-formed section rails supported on either cold-formed posts or hot-rolled steel posts. The most common rail is the standard section motorway vehicle restraint, with open box beams of trapezoidal section and sigma section also used. The posts can be subdivided into three further categories of stiff, fully welded construction of post with its base; intermediate stiffness posts incorporating a rubber energy-absorbing buffer between the post and its base, and flexible posts of curved spring steel construction.

The third type is of monolithic concrete construction with continuity reinforcement between the wall and floor deck. The majority of load is carried by cantilever action, though in some cases the vehicle restraint acts as a three-side supported slab. The relative rigidity and greater mass of this type of vehicle restraint means that it relies on the momentum at impact being distributed throughout much of the car park structure and energy being absorbed by elastic strain energy.

4.0 Vehicle Barrier Forces Over the Years

International Building Code (USA)

Code version	IBC 2000	IBC 2003	IBC 2006	IBC 2009	IBC 2012	IBC 2015	IBC 2018	IBC 2021
Code section	§1607.7.3	§1607.7.3	§1607.7.3	§1607.7.3	-	§1607.8.3	§1607.9	§1607.10
Load	6000 lbs.	6000lbs.	6000lbs.	6000lbs.	-	6000lbs.	6000lbs.	6000lbs.
Height above floor	1'-6"	1'-6"	1'-6"	1'-6" 2'-3"	-	Per §4.5.3 of ASCE 7-10	Per §4.5.3 of ASCE 7-16	Per §4.5.3 of ASCE 7-16
Area of application	1 sq. ft.	1 sq. ft.	1 sq. ft.	1 sq. ft.	-			

ASCE 7 (USA)

Standard version	ASCE 7-10	ASCE 7-16	ASCE 7-22
Section	§4.5.3	§4.5.3	§4.5.3
Load	6000lbs.	6000lbs.	6000lbs.
Height above floor	1'-6" 2'-3"	1'-6" 2'-3"	1'-6" 2'-3"
Area of application	12in x 12in	12in x 12in	12in x 12in

5.0 Rational Method for Barrier Design[5]

In Structure magazine, October 2008, an algorithm based on energy principles and empirical car crash data, showed that the impact force depends on four factors: mass, speed, and crush characteristics of the vehicle and barrier stiffness. The article concluded that the impact force on a barrier during a head on collision can be significantly larger than the code-specified force of 6,000lbs.

In a parking structure, barriers are used to prevent vehicles from plunging to the street below. Generally, the barriers are passive structures, such as concrete walls, upturn beams, spandrel beams, steel guardrails, bollards, and prestressed cables. If the vehicle can go through or over an obstacle, the obstacle is not considered an effective barrier. A barrier either fails during an impact with a colliding vehicle, or flexes so much that the vehicle breaches it without stopping.

The U.S. military has used field testing to design barriers used to protect its bases against enemy vehicles. The testing method may require building a teat barrier, subjecting it to a moving vehicle at a specified speed, and then standardizing it on a scale of 0 to 10. For example, the in the Military Field Manual, steel pipes embedded in 4-foot deep footings (Fig 3) have been approved for 4,500 pound vehicles travelling at 30 mph. And the protection rating of this system is given as 1.0, which is poor. Recently, the ASTM F-2656-07, *Standard Test Method for Vehicle Crash Testing of Perimeter Barriers*, has been developed to standardize the testing of barriers, which is a definitive approach but is expensive.

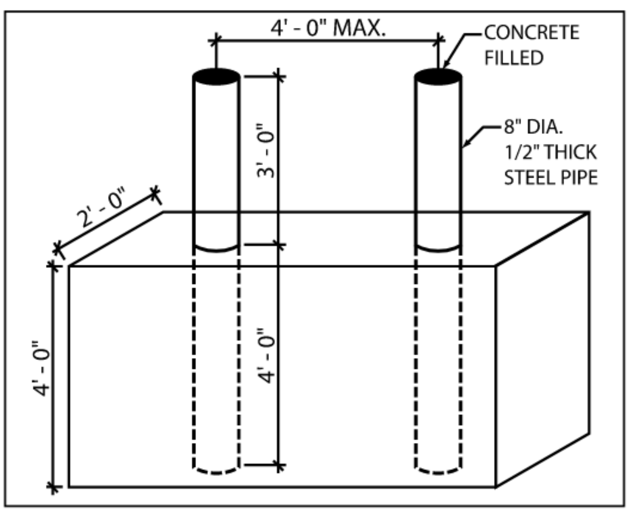

Fig 3: Steel bollards used as Barriers for 4500 lbs. vehicle travelling at 30mph[5].

In contrast, the proposed approach integrates energy principles with available crash data to determine the impact for force all types of barriers.

The proposed equation is as follows:

$$F = \frac{\mathrm{m}v^2}{2(c+b)}$$ ………..Equation (1)

Where m is the vehicle mass (=W/g, W being the weight, and g the acceleration due to gravity),

,v is the vehicle speed at impact, c, the vehicle crush, b the barrier deflection under impact.

Vehicular Speed

This is the most significant parameter affecting the impact force since the impact force increases with the square of the vehicular speed. This speed is a function of the vehicle acceleration.

Vehicle Crush

When a vehicle hits a barrier, parts of the vehicle deform, bends or crushes, and the vehicle length decreases. This decrease in vehicle length after an impact is termed "vehicle crush" i.e., term "c" in Equation 1. Based on the National Highway Traffic Safety Administration (NHTSA) vehicle crush distance "c" can be approximated by the equation:

$$c = \frac{\sqrt{v}}{3} \qquad \text{...........Equation (2)}$$

Where, v is the car speed in miles per hour (mph) and "c" is the vehicle crush in feet (ft.).

Since vehicles are manufactured by many automakers and in many models with changes made almost every year, the equation may need to be updated accordingly.

Barrier Deflection

During an impact, part of the vehicle's kinetic energy is transferred to the barrier. For barriers exhibiting linear behavior, the deflection can be represented as:

$$b = \frac{F}{\mathrm{k}} \qquad \text{...........Equation (3)}$$

Where, k is the barrier stiffness, and F is the impact force.

Combining equations 1, 2, and 3 and using some algebra, with g the gravity acceleration in ft/s^2, the following equation was developed:

$$F = 0.5\mathrm{k}[-\frac{\sqrt{\mathrm{v}}}{3.64} + \sqrt{\frac{2mv^2}{k.g} + \frac{v}{13.25}}] \qquad \text{.............Equation (4)}$$

Where m, k, and v are in ft-lb units, g is in ft/s^2 units.

Impact Results

Fig. 4 below shows the relationship for a 4,000-pound car impacting against a barrier of various stiffnesses, k. The figure shows that the impact force decreases as the barrier stiffness is reduced, however, barriers must have a limited stiffness to be effective, and not have excessive deflection upon impact. However, the impact force and associated deflection is not a straightforward task, for a non-rigid barrier, it may require consideration of the P-Delta effects. For example, the prestressed cable barrier system is a non-linear system that requires an iterative process to determine the impact load and the barrier deflection.

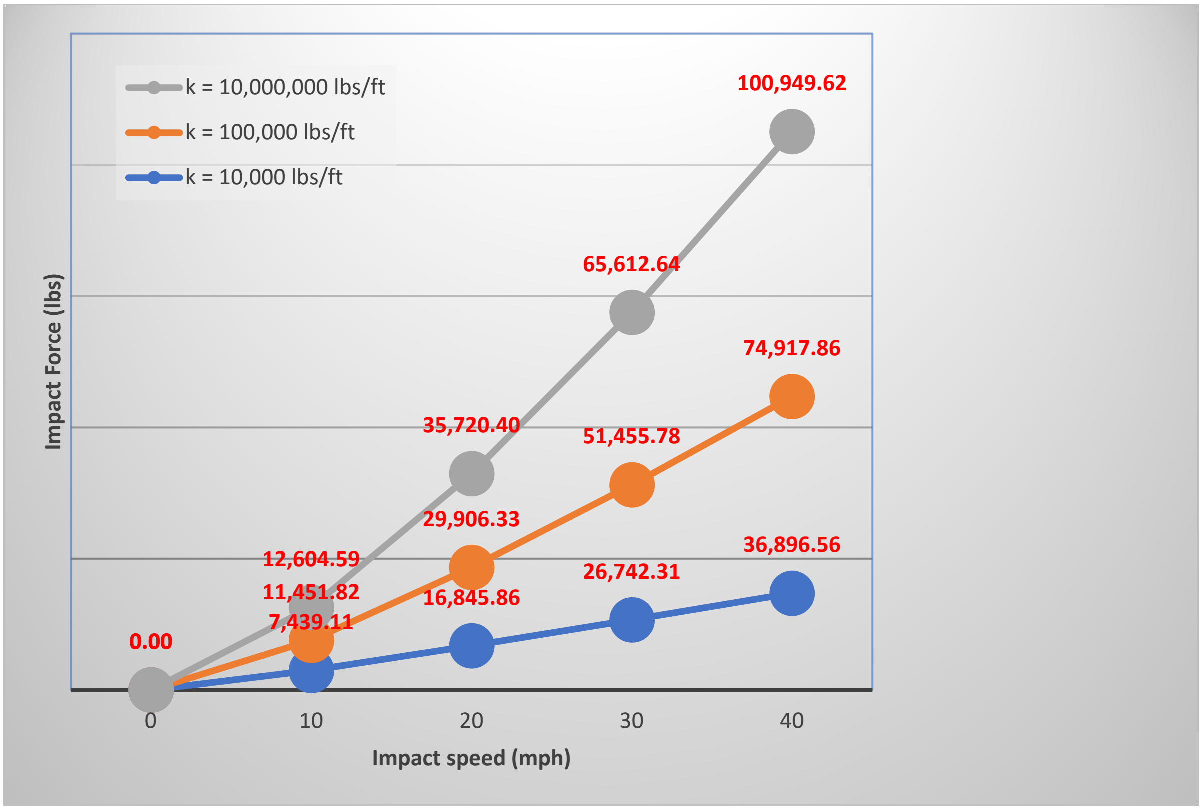

Fig 4: Vehicular Speed-Impact force plot for a 4000 lbs. vehicle with barrier stiffness, k.(NTS)

6.0 Barrier Force Determination in Other Jurisdictions

United Kingdom[6]

BS 6399: Part 1:1996

The horizontal force, F (in KN), normal to and uniformly distributed over any length of 1.5 m (4.95 ft) of a barrier for a car park, required to withstand the impact of a vehicle is given by:

$$F = \frac{\mathrm{m}v^2}{2(c+b)}$$

where m is the gross mass of the vehicle, (in Kg); v is the velocity of the vehicle (in m/s) normal to the barrier; c, is the deformation of the vehicle (in mm), and b, is the deflection of the barrier (in mm).

It should be noted here, this equation is identical to the one presented earlier in the paper from section 4, above. The code limits the gross mass of the vehicles in a carpark to 2,500kg (5,500 lbs.).

And "c" is limited to 100 mm (3.9 inches) unless better evidence is available, and "v" is given as 4.5 m/s (14.85 ft/s or 10.12 mph). For a rigid barrier, "b" is taken as zero. The mass is 1,500kg (3,300 lbs.) which in the UK is taken as more representative of the vehicle population than the 2,500 kg. However, with a rigid barrier, and mass 2,500kg, the force F is 150 kN., (33,000 lbs.).

The code also states, for car parks designed for a gross mass that exceeds 2,500kg., the actual mass is used with the same "v" and "c". This impact force is to be applied at a height of 375mm (14.7 in.) above floor level for cases where the vehicle class does not exceed the 2,500 kg.

Europe

Eurocode BS EN 1991-1-1:2002[7]

Forces on vehicle barriers and parapets for car parks are given in Annex B of the code and is identical to the BS 6399: Part 1: 1996 given above.

EC 1 1-7, 2003. (Eurocode)[7]

Annex C of this code gives a simplified procedure for dynamic calculation of the problem. In the case of a hard impact, with the impacting object deforms linearly during the impact phase, the following expression is used to determine the maximum force of interaction:

$$Fmax = v\sqrt{k.m}$$

where k is the equivalent stiffness of the colliding object. A typical value of k = 300 kN. /m (20,000 lb./ft) is also provided in the Annex.

German regulation[8]

DIN 1055-9:2003-08 Actions on structures. Accidental actions "(DIN 1055-9: 2003) sets a horizontal load to represent different types of impacts. For parking, it differs depending on the mass of the vehicle. For a mass of less than 2.5 tonnes (2,500 Kg), the equivalent static load in the direction of the road is 40kN (8,800 lbs.), while for a greater mass, this load is 100kN (22,000lbs.).

7.0 Acceleration Determination for EVs versus ICEs

The acceleration was based on a calculation with a time achieved for a 0 mph to 60 mph speed. The motion was assumed to be uniform since the time for the calculation was relatively small. So, the acceleration was calculated as the final speed, divided by the time taken to achieve the speed. The speed of 60 mph was converted to be equivalent to 88.0 ft/ sec. See Tables below for the data.

EVs[9]

Vehicle name	Model year	Final speed/ ft/s	Time /sec	Acceleration / ft/s^2
Rimac Nevera	2021	88.00	1.74	50.57
Tesla Model S Plaid	2021	88.00	1.98	44.44
Tesla Model S P100 D	2017	88.00	2.28	38.60
Porsche Taycan Turbo	2020	88.00	2.4	36.67
Tesla Model S	2020	88.00	2.4	36.67

ICEs[9]

Vehicle name	Model year	Final speed/ ft/s	Time /sec	Acceleration / ft/s^2
Porshe 911 Turbo S	2020	88.00	2.10	41.90
Bugatti Chiron Super Sport	2021	88.00	2.2	40.00
Lamborghini Huracan Performante	2018	88.00	2.2	40.00
Nissan GT-R Nismo	2020	88.00	2.48	35.48
BMW M8	2019	88.00	2.5	35.20

These accelerations can be used to calculate the impact velocity for the various vehicles, which can be used to calculate the impact force as given in the previous sections of this report.

8.0 Impact Velocity Calculations for the Vehicles in the Tables in Section 7

The impact velocity is calculated based the distance travelled by the vehicle, and the acceleration of the vehicle. The initial velocity is assumed to be at rest (0 mph). The equation used was:

$$v^2 = u^2 + 2ax$$

where "v" is the impact velocity, "u" is the initial velocity, "a" is the vehicle acceleration, and "x" is the distance travelled. From the reference 10 document, the general siting criteria for the pipe bollards are as follows:

- 6' center to center spacing (bollard spacing)
- 18 inches from the face of curb

The Tables below summarizes the impact velocities for the various vehicles. Note the impact velocities are well within the UK code value of 14.85 ft/sec (10.12mph).

EVs

Vehicle name	Model year	Acceleration / ft/s^2	Distance /ft	Impact velocity /ft/s
Rimac Nevera	2021	50.57	1.50	12.32
Tesla Model S Plaid	2021	44.44	1.50	11.55
Tesla Model S P100 D	2017	38.60	1.50	10.76
Porsche Taycan Turbo	2020	36.67	1.50	10.49
Tesla Model S	2020	36.67	1.50	10.49

ICEs

Vehicle name	Model year	Acceleration / ft/s2	Distance /ft	Impact velocity /ft/s
Porshe 911 Turbo S	2020	41.90	1.50	11.21
Bugatti Chiron Super Sport	2021	40.00	1.50	10.95
Lamborghini Huracan Performante	2018	40.00	1.50	10.95
Nissan GT-R Nismo	2020	35.48	1.50	10.32
BMW M8	2019	35.20	1.50	10.28

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