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A simulation study on quantifying damage in bridge piers subjected to vehicle collisions

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Abstract

Vehicle collision on bridge piers is no more a rare possibility with crowded city roads, encroached spaces, and lack of recommended margins around piers. An attempt is made through this study to investigate the plasticity induced in a pier due to a colliding vehicle. Responses of several piers with varying geometries are studied by finite element analysis. The piers are subjected to collision loads, static as well as dynamic in nature. The study aims at identifying the areas of damage and roughly estimating the damage sustained by the pier under consideration. A range of results in the form of graphs have been presented. Subroutines capable of handling material nonlinear effects in the static as well as dynamic zones were developed using MATLAB. The programs were validated using ANSYS. Separate results are presented for static and dynamic analysis. The forces considered for static analysis are based on specifications of several countries, while the force-time histories adopted for transient elastoplastic response of the pier are adopted from simulated crash test results. An attempt is made to get a better insight into quantifying damage with plasticity as an indicator.

Keywords: Collision, Impact force, Yield criterion, Convergence, Damage

Introduction

Encroachment on the minimum specified setbacks leads to extremely vulnerable piers to collision from the vehicles passing underneath. Although rare, such accidents can have serious implications in terms of loss of human lives and economy. Collision analysis in customary design is normally tackled by employing a static analysis of the pier. Specifications related to vehicle collisions on bridge piers owe their genesis to research conducted in the past and traffic-related statistical studies and accidents reported. Economics and risk factors also play a role in the formulation of specifications worldwide. At the same time, a collision force is highly dynamic in nature. The collision time is extremely small and involves a very large variation in the force with respect to time.

A study of the literature review can be broadly summarized into two parts, i.e., the force considered to be static and that considered as dynamic. As the actual scene of collision clearly demands the force to be a dynamic one, in customary design, a dynamic analysis proves to be cumbersome. Hence, several specifications advocate the use of static analysis. The study encompasses the specifications of several countries including the UK, the Netherlands, and the USA, and the Indian Roads Congress (IRC) (Dawe 2003; Indian Roads Congress 2006; British Standards Institution 1998; Djelebov and Donchev 2008). All countries specify a static impact force applied at a height of 1.2 to 1.5 m from the ground. El-Tawil (2004) concluded an equivalent static force (ESF) for two types of trucks for various velocities. These are the 14-kN Chevy truck to represent light trucks and the 66-kN Ford truck to represent the medium-weight trucks. A comprehensive study (El-Tawil 2004) used inelastic transient finite element simulations to investigate the demands generated during collisions between vehicles and bridge piers. The author investigated the complexities on impact force demands, effect of heavier trucks, and detailing of impact. Another report (Buth et al. 2010), conducted under phase I of a multistate pooled funds project titled 'Guidelines for Designing Bridge Piers and Abutments for Vehicle Collisions,' starts with statistical data and detailed descriptions of accidents/mishaps of collisions on bridge piers reported. Several accidents involving large truck-tractor-trailer collisions with bridge piers are investigated

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Table 1 Dimensional details of piers for study - part I

Serial number	Referencing	Description	Dimensions (m)
1	SW1	Solid wall pier type 1	0.75 × 4.00 × 7.50 (ht.)
2	SW2	Solid wall pier type 2	1.00 × 5.00 × 7.50 (ht.)
3	SW3	Solid wall pier type 3	1.50 × 6.00 × 7.50 (ht.)
4	SC1	Solid circular pier type 1	1.00φ × 7.50 (ht.)
5	SC2	Solid circular pier type 2	1.50φ × 7.50 (ht.)
6	SC3	Solid circular pier type 3	2.00φ × 7.50 (ht.)
7	HC1	Hollow circular pier type 1	2.00φ_{outer} (1.00φ_{inner}) × 7.50 (ht.)
8	HC2	Hollow circular pier type 2	2.50φ_{outer} (1.50φ_{inner}) × 7.50 (ht.)
9	HC3	Hollow circular pier type 3	3.00φ_{outer} (2.00φ_{inner}) × 7.50 (ht.)

ht., height; φ, diameter of pier.

as part of this project. Information such as vehicle speed, weight, and bridge pier details are gathered. The study provides a detailed discussion on the strength of piers, the mode of failure, and bending and shear failures. The report presents the result of simulation analysis of vehicular impacts on bridge piers. For this, two heavy truck models were used, *viz.* a single-unit truck (SUT; 65,000 lb, with rigid and deformable cargo) and a tractor-trailer (80,000 lb, with rigid and deformable cargo). Finite element analyses are conducted to determine the impact force experienced by a bridge pier upon impact by a heavy truck.

The present study is an attempt to quantify the likely damage the pier exhibits. For this, the study is divided into two parts. In the first part, a range of static collision forces stated in the specifications of a few countries are applied to several geometries of piers. An elastoplastic response is recorded. The points exhibiting plasticity (likely damage) are identified and presented, while force-time histories of a medium-sized truck and a large single-unit truck are adopted in the second part. These force-time histories are established by simulation techniques of crash tests on rigid barriers and are put to use on predefined geometries of piers. A transient elastoplastic response is obtained by finite element analysis, and the region recording plasticity is identified. The prime subject of interest in the present work is the pier subjected to collision and not the colliding vehicle.

Methods

Pier models

Piers considered are of three types: solid wall (SW), solid circular (SC), and hollow circular (HC) piers. For the first part, i.e., the static analysis, the dimensional characteristics of piers under consideration are given in Table 1. Table 2 gives the details of the piers considered for study taking into account the dynamic force-time history, which is the second part. The sizes are selected considering the current specifications and the sizes obtained as a result of customary design of bridges so as to represent a significant variety of bridge supports.

A 3D eight-noded isoparametric formulation is used for all piers. The hollow piers generally have thick walls (0.5 m in this case), and hence, the use of a thin shell element is not found to be suitable. Figures 1, 2, and 3 show the discretization of the piers. The two-Gauss point quadrature rule is used. Every element has eight Gauss points. The aspect ratio of each element is almost equal to 1.

The collision force is considered to act in the 'X' direction, i.e., the traffic direction. The effect of bearings and the partial fixity offered by the resistance of the bearings are accommodated by applying lateral spring elements capable of resisting the displacement at the top, limited to the frictional resistance offered by the bearings. More precision modeling of bearings has little effect (El-Tawil 2004; El-Tawil et al. 2005). The mass-inertia effects of the superstructure and the pier are built in the algorithm.

Table 2 Dimensional details of piers for study - part II

Serial number	Referencing	Description	Dimensions in (m)
1	SW1	Solid wall pier type 1	1.00 × 5.00 × 7.50 (ht.)
2	SW2	Solid wall pier type 2	1.50 × 5.00 × 7.50 (ht.)
3	SC1	Solid circular pier type 1	1.50φ × 7.50 (ht.)
4	SC2	Solid circular pier type 2	2.00φ × 7.50 (ht.)
5	HC1	Hollow circular pier type 1	2.00φ_{outer} (1.00φ_{inner}) × 7.50 (ht.)
6	HC2	Hollow circular pier type 2	2.50φ_{outer} (1.50φ_{inner}) × 7.50 (ht.)

ht., height; φ, diameter of pier.

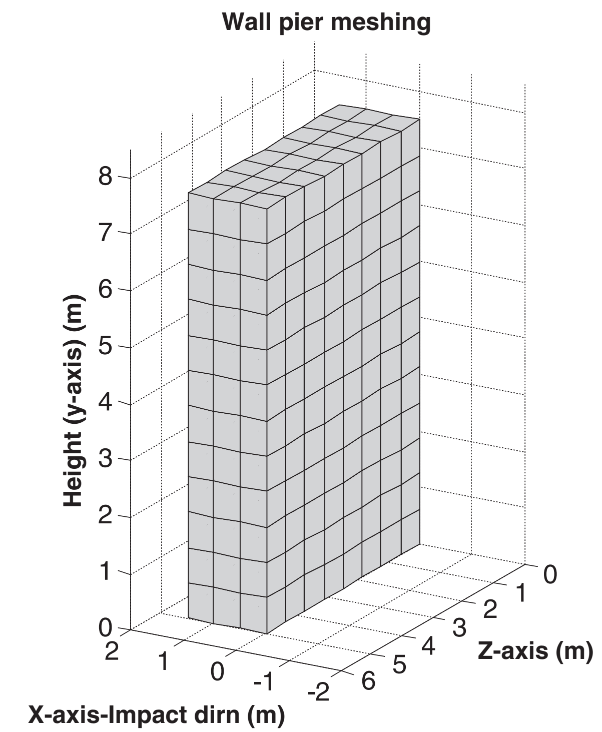

Figure 1 Meshing of solid wall piers.

The impact force is applied eccentrically on wall piers to simulate the actual accident, which may be rarely concentric.

Static impact force

The vehicular impact force is a dynamic force, but customary design practices consider it to be an ESF as

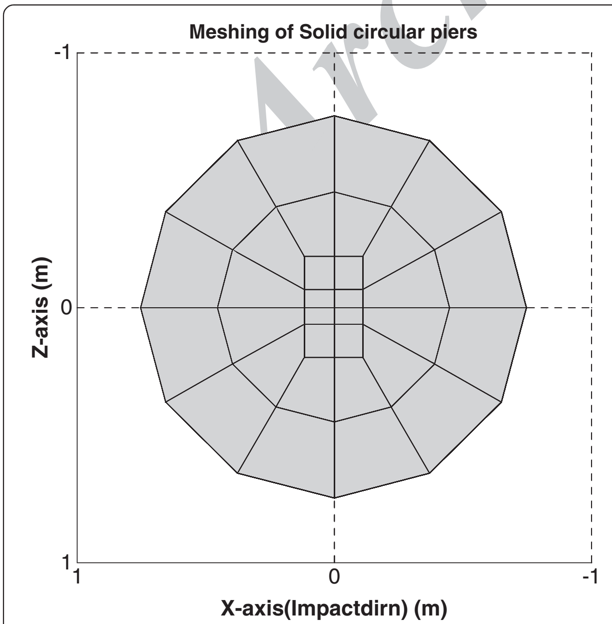

Figure 2 Meshing of solid circular piers.

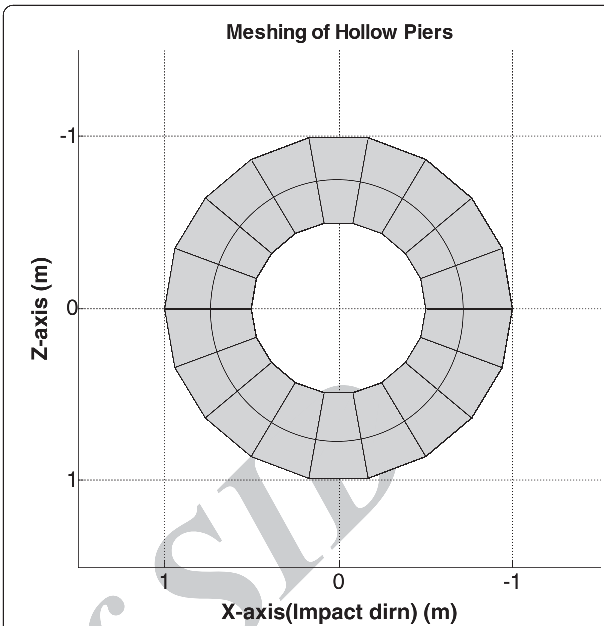

Figure 3 Meshing of hollow circular piers.

shown in Figure 4. The standards worldwide do recommend a static analysis and specify an impact force for the same. Vehicle collision force is laid down in specifications of countries like the UK, the Netherlands, the USA, and India. In addition, the ESF recommended by El-Tawil (2004) and El-Tawil et al. (2005) and the force of impact used in the provisions of BS 6779 (British Standards Institution 1998) have been included in the study. Table 3 gives magnitudes of the impact force and its point of application. Using BS 6779, the mass of the vehicle as actually observed on an Indian national highway (Table 4) has been used.

Calculation of design impact force due to vehicles plying Indian roads

Calculations of impact force at serial number 5 in Table 3 are shown in Table 4. Table 4 gives the static impact force as per 'Annexure A' of BS 6779: part I. The force is calculated for medium and heavy trucks using representative samples plying Indian roads. For this purpose, Equations 1 and 2 are employed (British Standards Institution 1998):

$$a = \frac{(v\,sin\theta)^2}{2[c\,sin\theta + b(\,cos\theta - 1) + z]}, \quad (1)$$

$$Mean\ \ impact force\ F(kN) = ma = \frac{m(v\,sin\theta)^2}{2,000[c\,sin\theta + b(\,cos\theta - 1) + z]}, \quad (2)$$

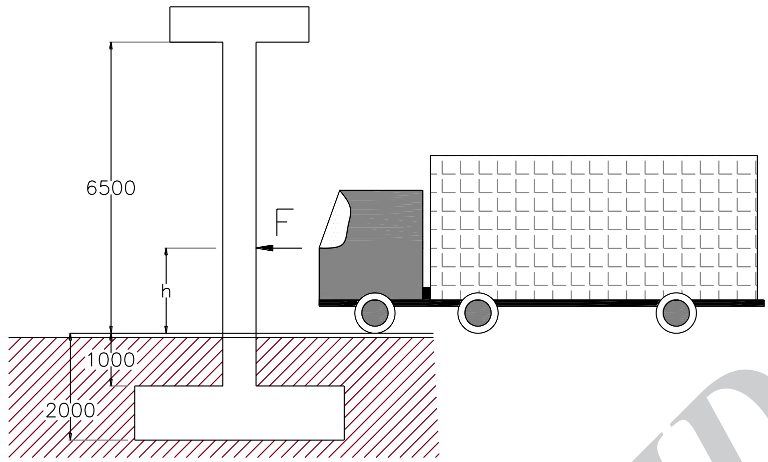

Figure 4 Sketch of a collision scene and the application of force.

where

- m is the mass (kg).
- b is half the width of the vehicle under consideration.
- c is the distance of the center of gravity, which largely depends on the goods being transported; here, it is considered to be located at half the distance of the trolley.
- v is the approach velocity of the vehicle considered which is 60 km/h (kph), i.e., 16.66 m/s (Indian Roads Congress 2006).
- z is the vehicle crumpling measured perpendicular to the barrier (m). The impact of a larger, heavier vehicle is likely to produce a larger value of z (British Standards Institution 1998). It is assumed that the cabin/frontal portion crumples on impact (El-Tawil 2004), in this case 1.42 m (Figure 5). The larger the crumple zone, the lesser is the impact force.
- θ is the angle between path of the vehicle and barrier at impact (°; refer to Figure 5). The angle at impact is assumed to be 90°, i.e., a head on collision to the pier, i.e., parallel to the direction of the traffic.
- a is the deceleration of the center of gravity of the vehicle.
- F is the impact force (kN).

Force-time histories and vehicle characteristics for dynamic analysis

Two types of force-time histories are considered for the study and are briefly described here along with some notable points. Commercial truck classification is determined based on the gross vehicle weight rating (GVWR). The force-time histories of class 6 and class 8 vehicles are considered (NTEA 2012).

Table 3 Impact force and its point of application

Serial number	Country	Reference			Force (kN)	Point of application from carriageway (m)	Direction of impact
1	UK and IRC	UKIRC			1,000	1.5	Parallel
2	Netherlands	NET			2,000	1.2	Parallel
3	USA	USA			1,800	1.2	Parallel
4	As per research (El-Tawil 2004; El-Tawil et al. 2005)	R1	Small truck	Circular pier	945	1.5	Parallel
		R2	Small truck	Rectangular pier	2,189		
		R3	Medium truck	Circular pier	3,700		
		R4	Medium truck	Rectangular pier	4,800		
5	Force as per actual traffic data of vehicles plying the Indian mainland roads	AF1	Sample 1	35-t truck	732	1.5	Parallel to carriageway
		AF2	Sample 2	40-t truck	836		
		AF3	Sample 3	68-t truck	1,243		
		AF4	Sample 4	177-t HGV	3,209		

HGV, heavy goods vehicle.

Table 4 Static impact force using Equations 1 and 2, i.e., as per BS 6779

Serial number	Mass (kg)	*b* (m)	*c* (m)	*v* (m/s)	*z* (m)	*θ* (°)	*a* (m/s^2)	*F* (kN)
1	35,200	1.25	6.500	16.66	1.42	90	20.806	732.38
2	40,200	1.25	6.500	16.66	1.42	90	20.806	836.41
3	68,700	1.25	7.500	16.66	1.42	90	18.094	1,243.03
4	177,400	1.25	7.500	16.66	1.42	90	18.094	3,209.80

Type 1

The force-time history for a medium truck (MT) with a GVWR of 11,900 kg (cabin load = 4,590 kg) and a wheelbase of 3,600 × 4,200 mm was obtained from a reputed vehicle manufacturing company with simulation techniques using LS-DYNA. The speed of the vehicle for a full frontal impact measures 48 kph on a rigid barrier. As crash tests are carried on rigid barriers, the dynamic force generated is maximum taking into consideration the plastic deformation of the vehicle while neglecting the flexibility of the barrier. Although flexibility of the barrier matters, several studies note its significance to be less in collision analysis (El-Tawil 2004). Figure 6 shows the force-time history considering the force till the recoil of the vehicle commences.

The conservation of impulse and momentum is checked. An error of 10.72% over the cumulative is recorded. This is found to be in line with similar observations in previous research works (El-Tawil 2004). Impact force at different speeds (i.e., 40, 50, and 60 kph) is derived from the force-time history (Figure 6). To cater to the variation in the force resulting from the variation in the speed of the vehicle, the impact force is proportionally increased. For this, the force-time history given in Figure 6 is considered as the base. This is reinforced by the conclusions drawn in the report by the Texas Department of Transportation, USA, wherein it is concluded that there is direct correlation between the force and the speed of the vehicle (approximately linear).

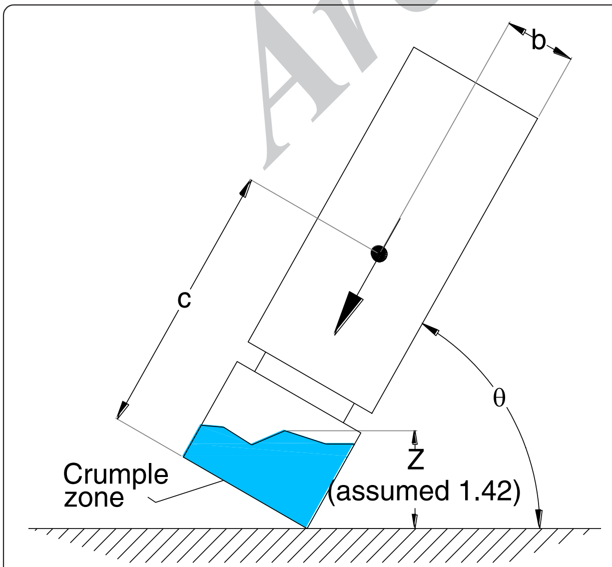

Figure 5 Vehicle with dimensions and angle of impact.

Type 2

The force-time history for a 30-tonner, large SUT was availed from the Texas Department of Transportation, USA (Buth et al. 2010). The authors of this report observed that simulation techniques are used to find the force-time history using a complex finite element model of the vehicle closely representing the actual vehicle. The prime interest was the force-time history for a 30-tonner. The force-time history due to the impact of a SUT (65,000 lb = 29,545 kg, say 30,000 kg) with a rigid cargo on a 1-m-diameter pier has been used in the present work. This is reproduced as Figure 7.

Based on the findings of the report, some of the salient points are enumerated which are used with the present work:

(a) The results of the analyses indicate that the diameter of the pier does not have a significant effect on the impact force exerted by a given truck and the speed.
(b) Three different speeds including 40, 50, and 60 mph were simulated. All of these analyses showed a direct correlation (approximately linear) between the impact force (maximum and the second peak) and the impact speed.

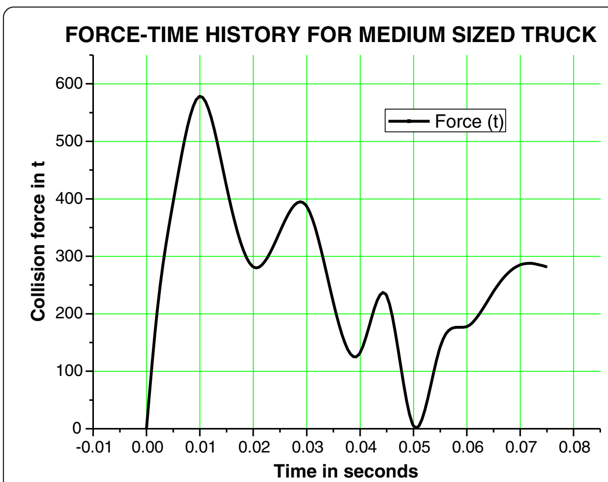

Figure 6 Force-time history for medium truck.

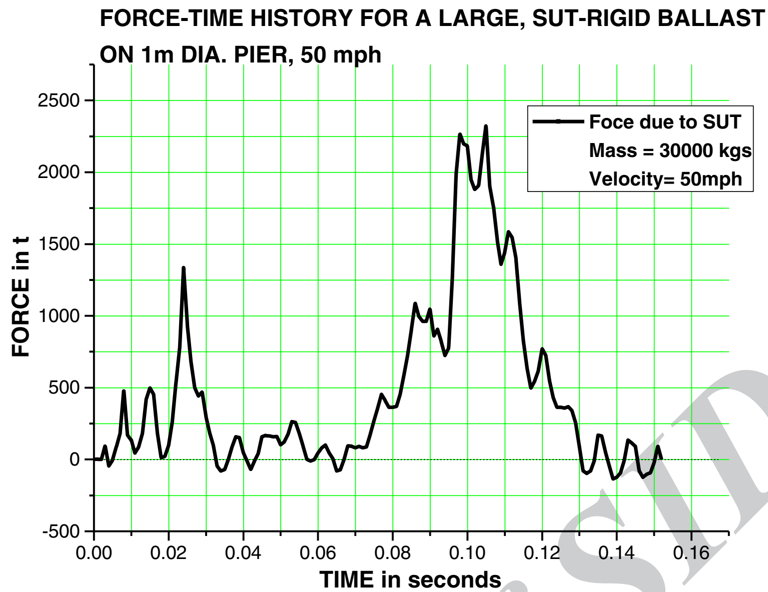

Figure 7 Force-time history for large truck (rigid ballast).

The force-time histories employed in this part of the study are built using these conclusions of the report referred above. Conservation of impulse and momentum is checked for this force-time curve.

Scope of work

Study part I

The first part of the study includes nine geometries of piers (Table 1) subjected to nine collision loads differing in intensity based on the selected specifications (Table 3). Thus, 81 cases are analyzed, and suitable predefined results are extracted. These results extend into the elastoplastic zone as well.

Notation used for identification of several runs of study - part I To simplify the notation to various combinations of force and type of piers, each run is allotted a unique reference system with the name indicating the

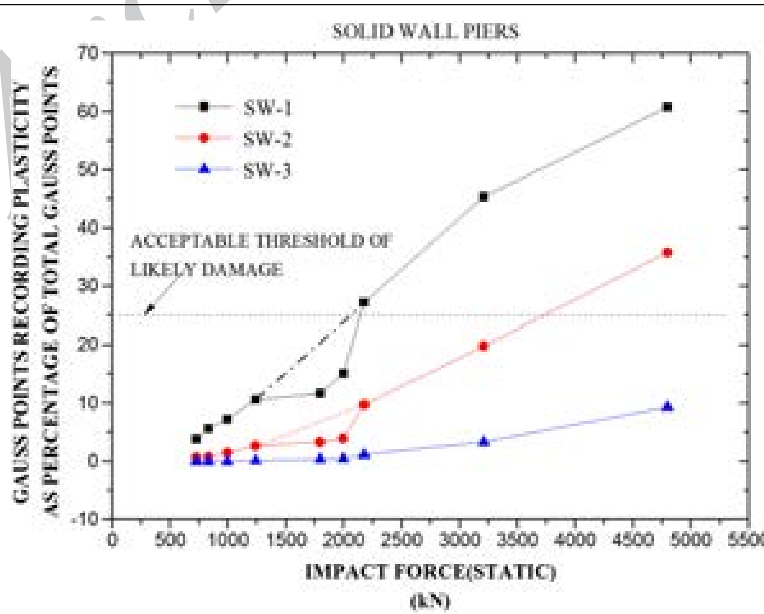

Figure 8 Plasticity recorded in solid wall piers.

main parameters of the corresponding run. For example, with reference to Table 3, if the loading is used as per Dutch specifications and the pier under consideration is a solid circular pier with a diameter measuring 2.0 m, then the run is referred to as NET-SC3. If the loading is derived from the representative samples (refer to Table 3 - serial number 5) impacting a wall-type pier measuring 4.0 × 0.75 m, then the run is referred to as AF1-SW1.

Study part II

The second part of the study encompasses six types of piers (Table 2), each with three grades of concrete. The grades are 40, 50, and 60 MPa. The piers are subjected to collision force from two types of vehicles, each travelling at three different speeds, *viz.* 40, 50, and 60 kph. A total of 108 cases are analyzed. This large data of 108 cases necessitated a unique identification nomenclature. The same is illustrated below with a few examples:

- W1G40MTV40 denotes *W*all pier type *1* with *G*rade *40*, *M*edium *T*ruck with *V*elocity *40* kph.
- SC1G50LTV60 denotes *S*olid *C*ircular pier type *1* with *G*rade *50*, *L*arge *T*ruck with *V*elocity *60* kph.
- HC2G60LTV50 denotes *H*ollow *C*ircular pier type *2* with *G*rade *60*, *L*arge *T*ruck with *V*elocity *50* kph.

Basics of elastoplasticity for finite element analysis

Problems related to collisions are nonlinear because with an increase in the force, the stress exceeds the yield stress and plasticity is induced. The stiffness becomes a function of displacement or deformation. The material is modeled as a homogeneous material wherein material properties such as nonlinear elasticity, plasticity, and creep are a function of the state of stress or strain (Cook 1981). The iterative Newton–Raphson method is adopted to handle the nonlinear effects exhibited by the material (Owen and Hinton 1980), i.e., concrete. This process is carried out by applying the external load as a sequence of sufficiently small increments so that the structure can be assumed to respond linearly within each increment (Arnesen et al. 1980).

Drucker-Prager yield criterion

The Drucker-Prager yield criterion is frequently used for soils, concrete, rock, and other frictional materials and is also used here. The Drucker-Prager yield constitutive law is expressed as

$$3aJ_1 + (J'_2)^{1/2} = k' \qquad (3)$$

The yield surface has the form of a circular cone. In order to make the Drucker-Prager circle coincide with the outer apices of the Mohr-Coulomb hexagon at any section, we get

$$a = \frac{2\sin\phi}{\sqrt{3}\times 3(3-\sin\phi)} \qquad (4)$$

and

$$k' = \frac{6.c.\cos\phi}{\sqrt{3}\times(3-\sin\phi)} \qquad (5)$$

Here, the material parameters c is the cohesion in concrete, and ϕ is the angle of internal friction. The relation

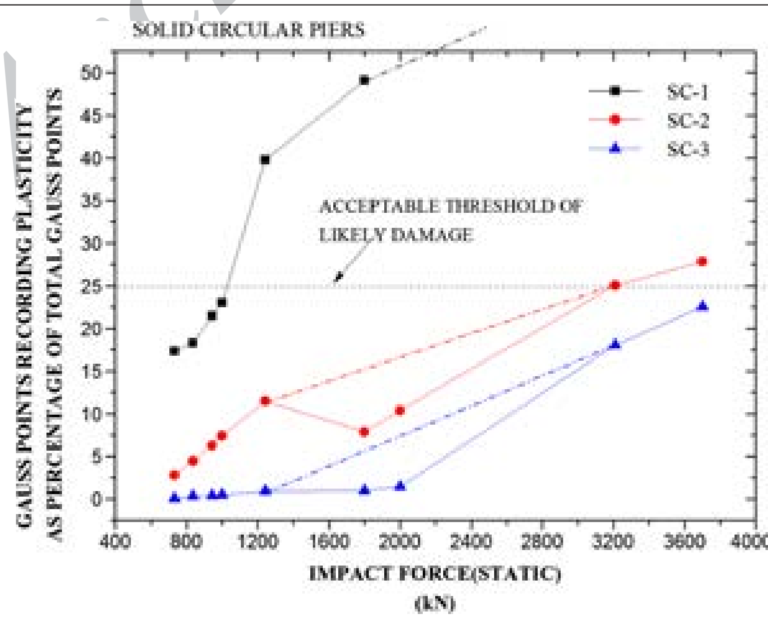

Figure 9 **Plasticity recorded in solid circular piers.**

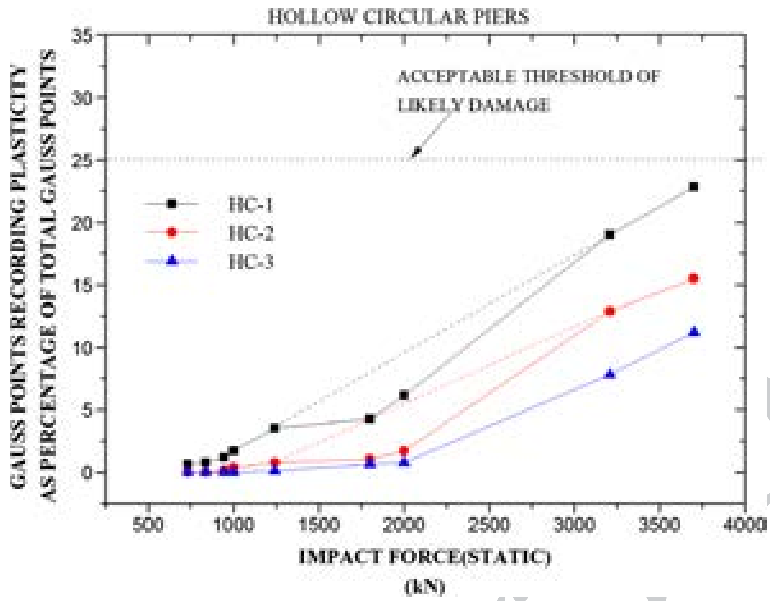

Figure 10 **Plasticity recorded in hollow circular piers.**

between these material parameters in terms of the compressive and the tensile strength of concrete (Lopez Cela 1998) is given as

$$\sin\phi = \frac{f_c - f_t}{f_c + f_t}, \qquad (6)$$

$$c = \frac{1}{2}\sqrt{f_c \cdot f_t}, \qquad (7)$$

where f_c is the compressive strength of concrete and f_t is the tensile strength that measures one tenth of the compressive strength. As the yield criterion records plasticity at a Gauss point, the contribution to stiffness has to be suitably reduced. This reduction is done through a flow rule (Owen and Hinton 1980). The element stiffness values are recomputed for the second iteration for each load increment except the first. This reduces the computing time considerably without any adverse effect on the accuracy of the results.

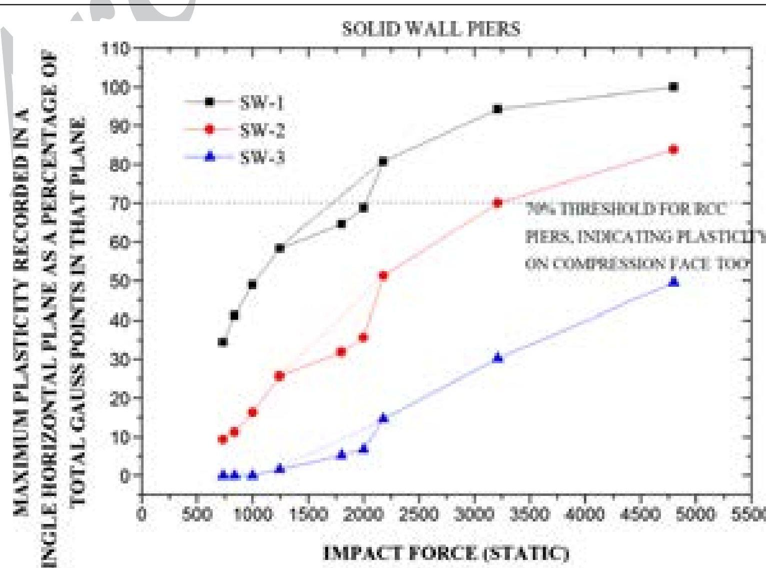

Figure 11 **Maximum plasticity in a single horizontal plane for solid wall piers.**

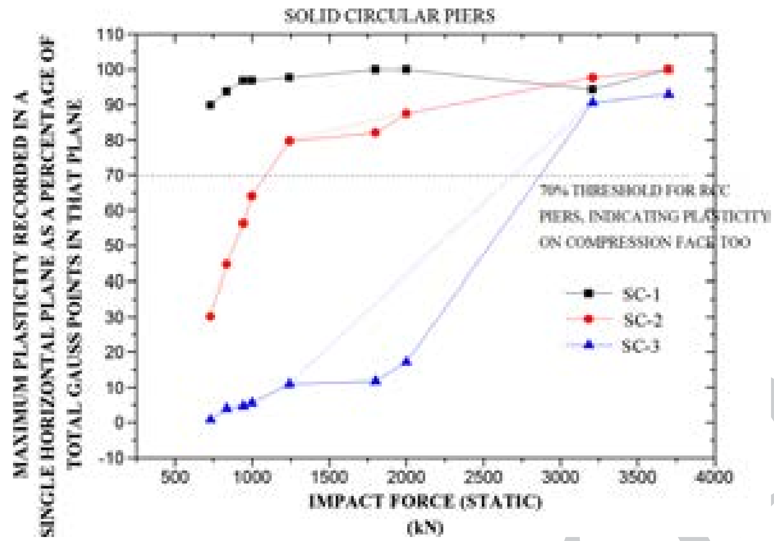

Figure 12 Maximum plasticity in a single horizontal plane for solid circular piers.

Mesh size and critical time stepping for dynamic analysis

It is well known that the finer the meshing of the structure, the more accurate is the result obtained, particularly in the case of nonlinear problems. A time interval of 0.0005 s is adopted for analysis of collision from MTs. For the force-time history of large trucks (LTs), sudden peaks and variations have compelled the use of a smaller time interval for a stable analysis. Hence, for LTs, the time stepping is set at 0.00025 s and the collision scene is investigated for 0.25 s.

Convergence criteria

As the program iterates, to improve upon the imbalance in the residual force and acquire a solution for the nonlinear problem, there is a need to monitor the numerical process by establishing some kind of a comparison between the values of unknowns determined during iterations. The convergence is checked in two ways, i.e., the displacement criteria (Owen and Hinton 1980; Bergan et al. 1978) and the residual force convergence method (Owen and Hinton 1980). Since the inertia of the system

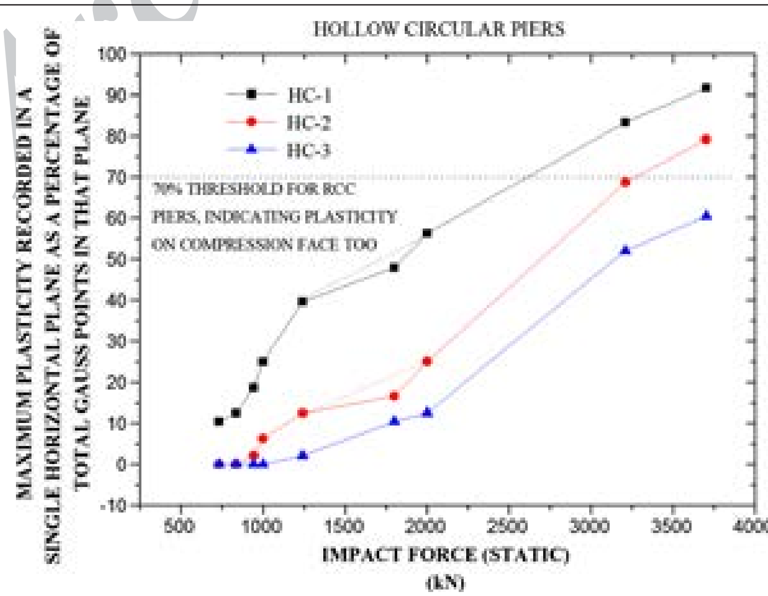

Figure 13 Maximum plasticity in a single horizontal plane for hollow circular piers.

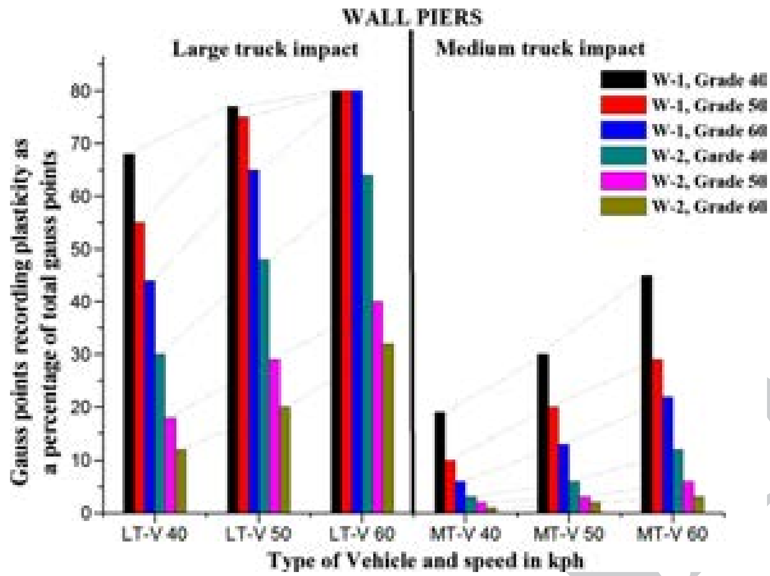

Figure 14 Plasticity recorded in solid wall piers for transient elastoplastic analysis.

renders its dynamic response, we get a 'more smooth' response than for a static analysis. It is observed that convergence for a transient analysis is more rapid than that for a static analysis (Bathe 2003) due to the effects of inertia.

Results and discussion

Part I of the study

Gauss points recording plasticity

The program records the history of Gauss points showing plasticity at every load step. Although plasticity cannot always be identified as the damage that the pier suffers post collision, it can be an indicator for a fair judgment. Figures 8, 9, and 10 are graphs drawn separately for SW, SC, and HC piers, respectively. The horizontal line is drawn at ordinate 25%, terming it as an acceptable threshold of likely damage. This is only a proposition.

There is a drop in the percentage of recorded plasticity from 1,800 up to 2,000 kN of force. This is because the point of application, as specified in the AASHTO code and the Dutch code, is 1.2 m instead of 1.5 m that is valid in the case of other selected forces (Table 3). The dotted line is added so as to recognize the quantum of Gauss points recording plasticity if the said force is applied at 1.5 m from the ground.

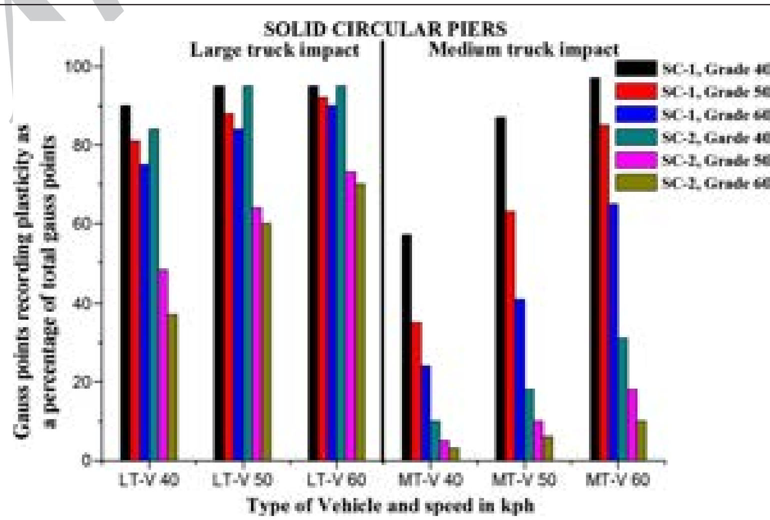

Figure 15 Plasticity recorded in solid circular piers for transient elastoplastic analysis.

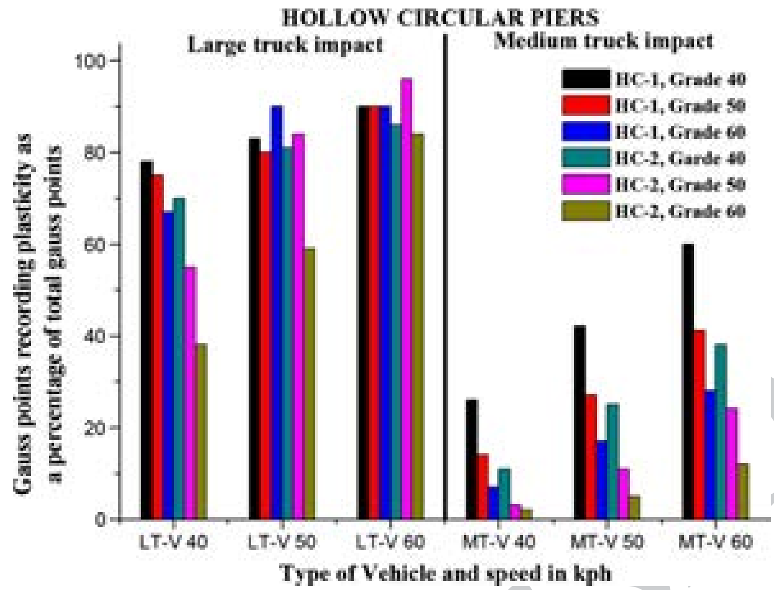

Figure 16 Plasticity recorded in hollow circular piers for transient elastoplastic analysis.

Maximum recorded plasticity in a single plane

The maximum number of Gauss points recording plasticity in a single horizontal plane is shown in Figures 11, 12, and 13. The number of Gauss points recording plasticity is extracted at each horizontal plane. The planes are defined as the pier is meshed into finite elements. The pier being an RCC section with the plasticity in its compression zone, i.e., at the face farther from the face of collision, proves to be decisive in assessing the damage from this simulation. The graphs are presented separately for all the three types of geometries of the pier. Each graph gives the maximum plasticity recorded in a single plane as a percentage of the total Gauss points in that plane. The threshold here is proposed as 70, i.e., 70% of the section of the pier enters the plastic zone, and it can be judged that the plasticity encroaches into the compression zone of the pier face making the structure unstable, thus bringing about a considerable reduction in stiffness due to cracking/micro-cracking, all adding up to indicate damage.

Part II of the study

Six types of piers, two each for all the three shapes, were analyzed to obtain the transient elastoplastic response of the piers. The results of the maximum plasticity recorded for the high quantum of impact force that may be expected are presented in the form of bar charts. Figures 14, 15, and 16 show the number of Gauss points recording plasticity as a percentage of the total number of Gauss points. The effect of the increasing grade of concrete is also presented.

Figures 17, 18, 19, 20, and 21 show the area exhibiting plasticity (darkened area). The region undergoing plasticity can be identified. The encircled nodes denote the patch of impact loading.

Conclusions

The collision on the pier may lead to damage that cannot be pinpointed as a scene of collision is unique in many respects and has to be treated so. The study is conducted

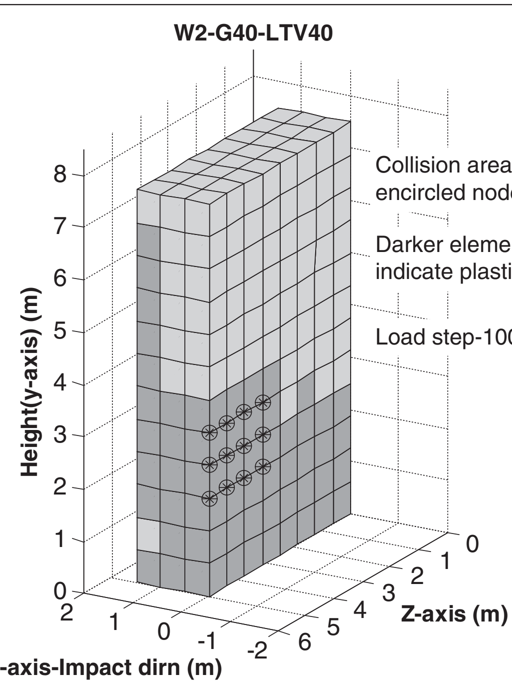

Figure 17 Plasticity in solid wall pier.

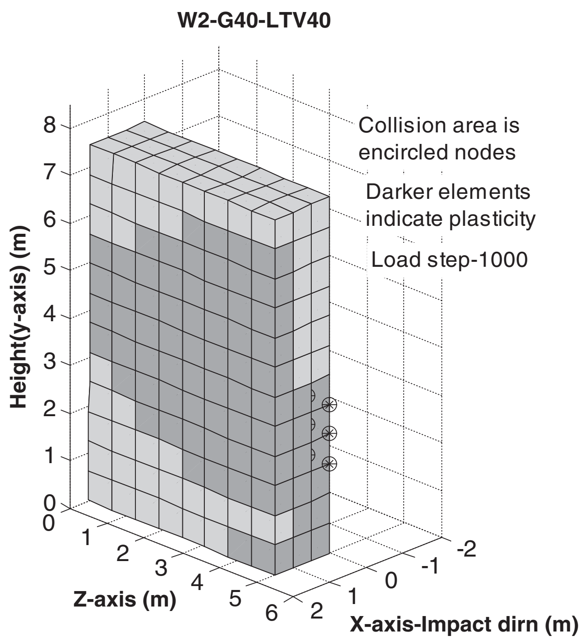

Figure 18 Plasticity in solid wall pier (axis rotated).

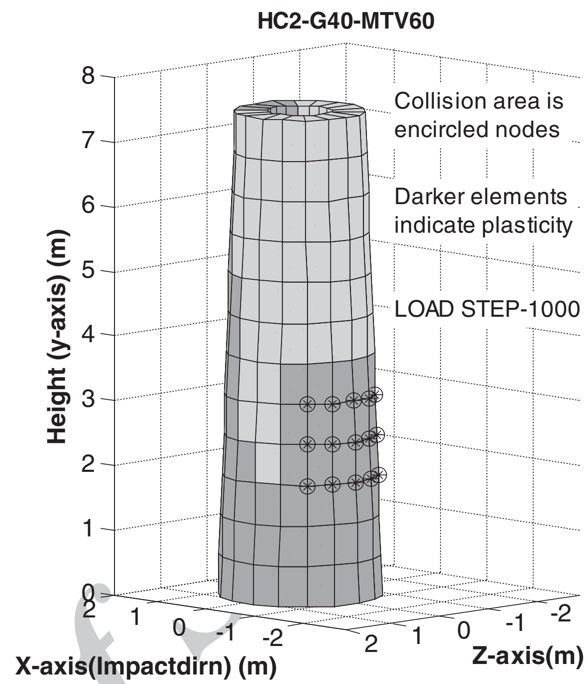

Figure 20 Plasticity in hollow circular pier.

keeping in view the major parameters involved in a bridge pier-vehicle collision. The expected damage can be assessed by observing the induction of plasticity. In the static zone, dual plasticity estimation is proposed as it provides vital information on the expected damage. The suitability of a particular pier with reference to the tonnage of vehicles likely to pass the road can be judged from the results presented here. Quantifying damage is a very complex task. However, a proposition is made in this regard. The threshold suggested is subject to change, but at the same time, the graphical representation indicating the plasticity in percentages can be put to use while deciding on the size or the shape of the pier. Dynamic analysis for large-truck collisions indicates that

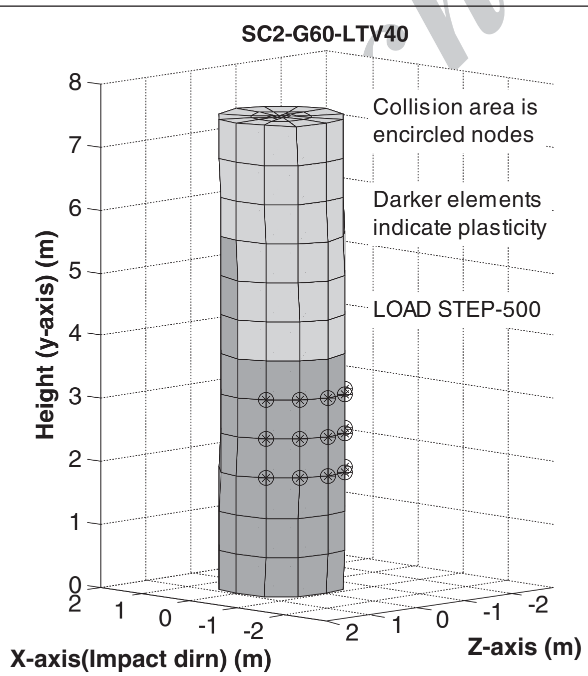

Figure 19 Plasticity in solid circular pier.

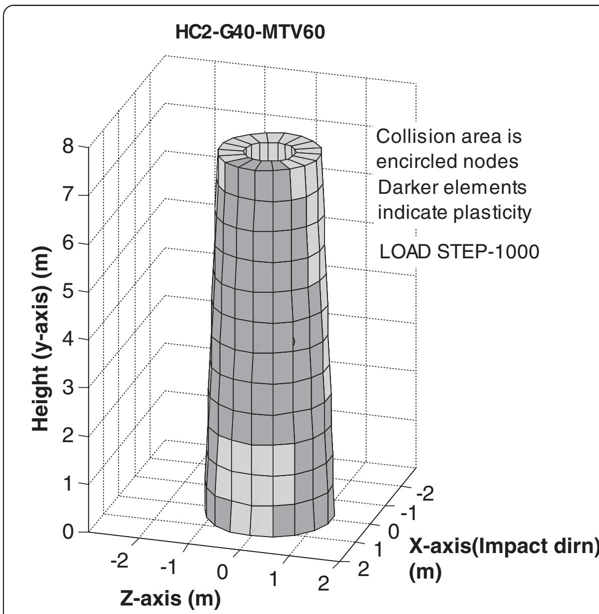

Figure 21 Plasticity in hollow circular pier (axis rotated).

most of the piers record severe damage. This highlights the need for a meticulous approach in the design of piers where such traffic is expected. In addition, speed restrictions may prove effective. The medium-truck collisions are less severe. The enhancement of the grade of concrete from 50 to 60 MPa adds more to the performance than the enhancement from 40 to 50 MPa. The suitability of the pier can be judged by observing Figures 14, 15, and 16 depending on the shape of the pier.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
AJ and LG contributed equally on all aspects of the work. It is a joint effort. Both authors read and approved the final manuscript.

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