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NUMERICAL SIMULATIONS OF METALLIC FOAM SAFEGUARDED RC SQUARE COLUMNS UNDER LATERAL SOFT IMPACT

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Abstract: When a truck impacts on a reinforced concrete (RC) column such as a bridge pier at a high velocity, a large reaction force would generate which would damage the truck, hurt the passengers and destroy the column. Lightweight foams with excellent energy absorbing performance are often used as safeguard constructions to resist impact. The impact behavior can be divided into soft and hard impact. In the case of soft impact, the impacted structure deformation is predominant. In the paper, metallic foam safeguarded RC square columns impacted by a rigid block are simulated using the ABAQUS code software, and the influential characteristic of foam density on the peak impact force and ultimate energy absorption is focused on. The simulated results indicate that the foam safeguard constructions play remarkable role on impact resistance. It is exciting that there appears almost an identical critical foam density corresponding to the minimum peak force and the ultimate energy absorption, which is of great significance for engineering design of this type of safeguard constructions to resist impact.

Keywords: Metallic foams; RC columns; Impact resistance; Numerical simulation.

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1. INTRODUCTION

As the traffic develops rapidly, the possibility of vehicle collision with RC columns such as bridge piers rises considerably. When a truck with heavy load hits a RC column at a high velocity, a large impact force would generate which perhaps causes the truck damaged, the passengers hurt and the column destroyed. Vehicle impact with RC columns was usually investigated by simulation and/or experiment due to parametric complexity.

Some buildings are just close to busy roads, and the concrete columns of which on the ground floor have much possibility subject to vehicle impact in an accident. The capacity of a reinforced concrete column of a building in resisting vehicle collision was investigated using nonlinear static analysis, and the influence of velocity-time function and vehicle stiffness was studied [1]. Probabilistic modeling of vehicle impact on concrete columns came to a conclusion that deterministic modeling would considerably underestimate impact forces [2]. The influence of different combinations of parameters including concrete grade, steel amount, slenderness ratios on vehicle impact with concrete columns was investigated to identify the means to mitigate damage [3]. A nonlinear explicit numerical model was established to assess the vulnerability of concrete columns to vehicle impacts, and an analytical method was presented to predict the impact response [4].

Bridge piers across crowded roads have more and more probability of suffering vehicle collision, which maybe result in great economic and human losses. Several piers with various geometries subject to vehicle collision were investigated using finite element analysis to identify damage areas and quantify damage using plasticity as the index [5]. A nonlinear computational model of a truck impacting a concrete pier revealed that the resultant impact force is two times, six times higher than that obtained from dynamic analysis and the equivalent static force, respectively, which were calculated based on the European standard EN 1991-1-7[6]. Sharma etc. al [7] proposed a procedure to estimate the dynamic shear capacity of an RC column subjected to vehicular impact for different performance levels. Furthermore, they suggested a probabilistic model to accurately predict the dynamic shear force demand on the RC columns, based on which a framework for the performance-based analysis and design of RC columns were developed to estimate the fragility of the RC columns [8]. Chen etc. al [9] developed and validated an equivalent truck frame to model the response of a large-size truck impacting an RC column for reducing the difficulty and cost of performing full-scale impact tests. In addition, they proposed a reduced mass-spring-damper coupled model to model the impact process, which was calibrated and verified against the results from finite element simulation [10]. A novel equation of design impact force of vehicle impact with RC bridge columns was presented based on an extensive finite element analysis including 13 parameters study, which demonstrated more accuracy than the results from Eurocode and American Association of State Highway and Transportation Official-Load and Resistance Factor Design [11]. A numerical model of vehicle collision with bridge piers was developed and validated considering the strain rate effect using LS-DYNA, which concluded that the equivalent static force in the current main standards was un-conservative and unreasonable against the numerical results [12]. Based on numerical simulation results, the peak impact forces of vehicle impact with RC columns were found to be governed by the engine's weight except for the total vehicle mass and the vehicle velocity and to remarkably affect the column axial force [13].

Concrete is a typical brittle material, which is prone to damage under impact force. For the safety of the RC columns to resist impact, it is a feasible option to cover safeguard constructions around the columns with energy absorption materials. Lightweight foams with excellent energy absorption performance such as metallic foam, PVC (polyvinyl chloride) foam and carbon foam etc. are often used as energy absorbing constructions. It was found that dynamically loaded sandwich beams with open-cell metal foam cores demonstrated several failure modes, such as face wrinkle, core shear and large inelastic deformation [14]. A number of tests on impact response of sandwich composite panels with PVC foam core were conducted, and the primary damage modes including fiber fracture at skins, delamination between adjacent layers, core shear fracture and face/core debonding were observed [15]. Reyes etc. al studied the fracture properties of high performance carbon foam sandwich structures, and found that these lightweight sandwich structures have excellent load bearing capacity before fracture [16].

The impact behavior could be divided into hard and soft impact. For the hard impact, the impacted constructions are considered as stiff and unmoved, while only the impacting vehicles generate deformation. Conversely, the soft impact implies that the impacted constructions deform only [6]. In fact, when a vehicle impacts a RC column, the deformation of the vehicle and the column dominates at the earlier and later stage, respectively. In other words, the hard impact and soft impact dominates at the earlier and later stage, respectively. Considering the safety of RC columns, investigation on the soft impact makes more sense. For simplicity, the impacting vehicle is reduced to rigid “truck” in this paper, which is the most potential vehicle type causing the RC column damage. In addition, the assumption of “Rigid truck” has an advantage of focusing on the column’s response without the influence of the truck deformation. Metallic foam is a typical lightweight foam material with outstanding energy absorbing capability, which is used as the energy absorbing material to safeguard the RC column to resist vehicle impact in the present analysis. Foam density is a crucial parameter to characterize mechanical properties of the foam such as elastic modulus, plateau stress and densification strain etc. The peak impact force and energy absorbing capacity are the two key factors for the protection of impacted constructions to resist impact. In the paper, nonlinear dynamic analysis on the metallic foam safeguarded RC square columns under lateral soft impact are conducted using ABAQUS explicit code, aiming to grasp the influential characteristic of foam density on the peak impact force and energy absorbing capability.

2. FINITE ELEMENT MODELS

2.1 GEOMETRIC CONFIGURATIONS

In the present analysis, a reinforced concrete square column with section 1.0m×1.0m and 5.0m in height is considered, as shown in Fig. 1. 16 longitudinal reinforcements with diameter 20mm are spaced evenly around the perimeter of cross section, and the concrete cover is 30mm. The transverse reinforcements with diameter 8mm are spaced at 200mm along axial direction of the column. The impacting truck has a rectangular head with size 1.5m×0.25m according to the literature [4]. The height of the impact point above ground is set 1.5m in agreement with the sixth edition of the American Association of State Highway and Transportation Officials-Load and Resistance Factor Design (AASHTO-LRFD) released in 2012 [17]. The safeguard construction with an identical thickness 0.4m and length 1.0m along axial direction of the column covers the column around the perimeter at the height of the impact point.

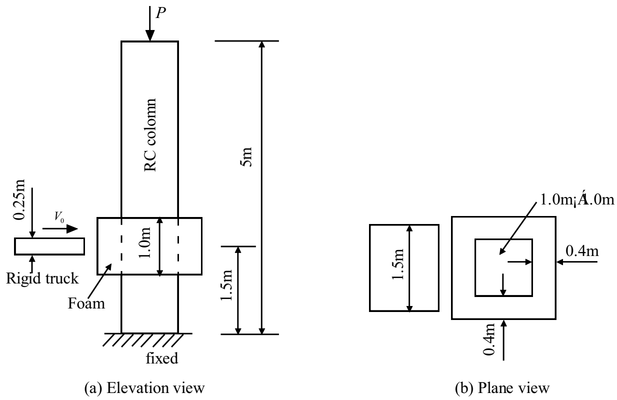

Fig. 1. The geometric configurations of rigid truck impact with foam safeguarded RC column

2.2 MATERIAL CHARACTERISTIC

The concrete grade is named C25, and the strength grade of the longitudinal and transverse reinforcements is called HRB400 and HPB300, respectively, see Table 1. The concrete property data are referenced from Abaqus Verification Guide, tabulated in Table 2 and

Table 3. The Young's modulus and yield stress of the reinforcements are listed in Table 4.

Table 1. The configuration of the piers simulated in the FE models

Cross-section	Cover	Concrete grade	Longitudinal reinforcements	Transverse reinforcements
1.0m×1.0m	30mm	C25	16 Φ 20 (HRB400)	Φ 8(HPB300)@200

Table 2. Concrete damaged plasticity data

Dilation angle	Flow potential eccentricity	Biaxial/uniaxial compression plastic strain ratio	Invariant stress ratio	Viscosity
15°	0.1	1.16	0.6667	0.0

Table 3. Compression and tensile properties of concrete material

Compression			Tension		
Yield stress/ MPa	Inelastic strain	Damage	Yield stress/ MPa	Cracking strain	Damage
24.019	0	0	1.780	0	0
29.208	0.0004	0.1299	1.457	0.0001	0.30
31.709	0.0008	0.2429	1.113	0.0003	0.55
32.358	0.0012	0.3412	0.960	0.0004	0.70
31.768	0.0016	0.4267	0.800	0.0005	0.80
30.379	0.0020	0.5012	0.536	0.0008	0.90
28.507	0.0024	0.5660	0.359	0.0010	0.93
21.907	0.0036	0.7140	0.161	0.0020	0.95
14.897	0.0050	0.8243	0.073	0.0030	0.97
2.953	0.0100	0.9691	0.040	0.0050	0.99

Table 4. Mechanical properties of the reinforcements

Category of reinforcements	Young's modulus/GPa	Poisson's ratio	Yield stress/MPa
HRB400	200	0.3	400
HPB300	210	0.3	300

The constitutive models for metallic foams were firstly presented by Deshpande and Fleck [18], and introduced into ABAQUS material library [19]. There are two plastic hardening models called volumetric hardening and isotropic hardening, which predict similar behavior for compression-dominated loading. In the models, the relationship of true yield stress to the corresponding logarithmic plastic strain under uniaxial compression needs inputting. The typical uniaxial stress-strain curve of metallic foams could be simplified to three stages, i.e. initial elastic stage, plateau stress stage and densification stage, as shown in Fig. 2, where σ_s refers to yield stress of the matrix material of the foam and E_c, σ_c, ε_d^i, ε_d^f denote the elastic modulus, plateau stress, initial densification strain and full densification strain of the metallic foam, respectively. The mechanical properties of metallic foams were generally thought to relate to its relative density and the mechanical properties of its matrix material, and some functions were suggested to describe the relationship in previous studies. For example, the relationship in the expressions of Eqs. (2.1)-(2.4) is well used, where the Eqs.(2.1), (2.3) and (2.4) are obtained from the study [20], while the Eq.(2.2) comes from the literature [21]. In these equations, the symbol E_s is the Young's modulus of the matrix material, and $\bar{\rho}$ represents the relative density of the foam, defined by the ratio of the density of the foam to that of its matrix material, i.e. $\bar{\rho} = \rho_c / \rho_s$. In the present analysis, he mechanical properties of foam calculated by Eqs.(2.1)-(2.4) are used, and the Young's modulus and yield stress of the matrix material of the foam are let be 94.1GPa and 111.4MPa, respectively [22]. Considering the impact speed is not very high, the influence of strain rate effect is thought of not to cause substantial change of the present resultant conclusions. For simplicity, no strain rate effect is considered in the present analysis.

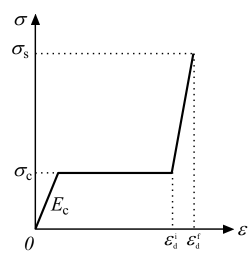

Fig. 2. Simplified uniaxial compression curve of foam materials

(2.1) $$E_c = E_s \bar{\rho}^2$$

(2.2) $$\sigma_c = \sigma_s \bar{\rho}^{3/2}$$

(2.3) $$\varepsilon_d^i = 1 - 1.4\bar{\rho}$$

(2.4) $$\varepsilon_d^f = 1 - \bar{\rho}$$

2.3 INTERACTION, LOAD, BOUNDARY CONDITIONS AND ELEMENT TYPES

The constraints between the two type of reinforcements and the concrete is defined using the Embedded Region technique, specifying the reinforcement elements that lie embedded in concrete elements whose response will constrain the translational degrees of freedom of the embedded reinforcement nodes. The Tie constraint is used to define the interaction between the column and safeguarded foam, which constrains each of the nodes on the foam surface to have the same motion as the point on the column surface to which it is closest. The tangential behavior of the contact surface between the truck and that of the foam is defined using Surface-to-surface contact with friction coefficient 0.3 according to the previous paper [11].

The impacting truck with mass 10t at an initial velocity of 60km/h perpendicular to the column axis impacts the RC column, which has fixed boundary condition at its bottom. The top end is hinged as assumed by Abdelkarim and ElGawady [23].The force loaded on the top of the column is 5% of the column's axial capacity P_0 in line with the study [11], and the column's axial capacity is calculated by [17]

$$P_0 = A_s f_y + 0.85\left(A_c - A_s\right) f_c' \tag{2.5}$$

where:

A_s– the total cross-section area of the longitudinal reinforcements, A_c– the cross-section area of the concrete column, f_y – the yield stress of the longitudinal steel reinforcements, f_c'– the cylindrical concrete's compressive stress.

In the numerical models, the column and foam elements are both modeled by C3D8R, meaning 8-node linear brick with reduced integration and hourglass control, while the reinforcement elements are simulated using T3D2, referring to 2-node linear 3-D truss. The element meshing size of various parts of the whole model is adjusted to meet convergence of the calculated results.

3. SIMULATION RESULTS

3.1 DYNAMIC RESPONSE

The safeguard structures aim to lower the truck velocity, offering safeguard for the column and the truck itself. Fig. 3 gives the truck velocity-time history varying with the foam density, where. For comparison, the naked column without any safeguard is also simulated. In Fig. 3, “NO Foam” means the naked column without safeguard, and “Foam01” refers to the relative density of the foam, and so on. It can be observed that the truck velocities with foam safeguard decrease much more rapidly than that for the case of the naked column, indicating that the foam absorb plenty of kinetic energy of the truck. In addition, at the initial stage, the velocities drop more quickly when the foam density is larger. At the later stage, the velocities for the various foam densities descend close to each other except for the foam01 with relative density 0.1.

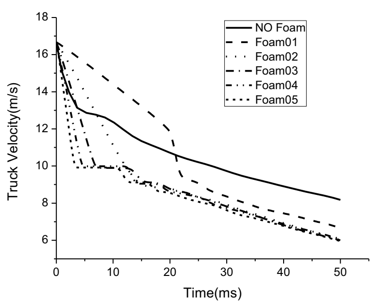

Fig. 3. The truck velocity-time history

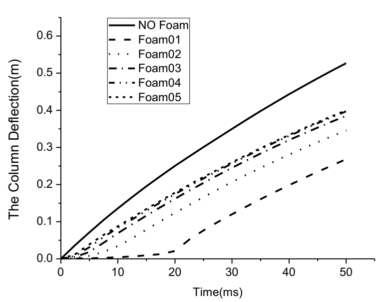

Fig. 4. The column deflection-time history along the impact direction

Fig. 4 gives the column deflection at the impact point varying with time, safeguarded by foams with various densities. For the naked column without safeguard, which needs absorb the impacting kinetic energy itself, the transverse deflection at the impact position equals to the truck displacement. It reveals that the deflection would be small especially at the initial impact stage when the density of foam is small. This is because the foam with small density has larger compressibility and deformation before densification.

The foams absorb the impacting kinetic energy through large deformation. In Fig. 5, the nominal compression strain, defined by the deformation in the impact direction normalized with the initial thickness of the foams 0.4m, has two typical deformation stages. At the first one, the strain increases with time, while later keeps a plateau constant corresponding to densification of foams. Furthermore, the ultimate strain decreases with the increase of the foam density due to more compressibility of lower density foam.

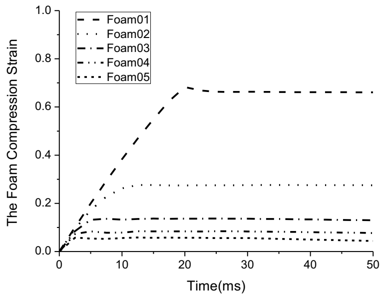

Fig. 5. The nominal compression strain of foams-time history

3.2 PEAK IMPACT FORCES

When the truck collides with the RC columns at a high velocity, a large impact force would act on the columns, which makes the columns deform, damage and collapse. Conversely, the large reaction force on the truck perhaps damages the truck and hurts the passengers. The response history of the resultant impact forces from simulation is demonstrated in Fig. 6, including the naked column and the columns safeguarded by the foams with relative densities 0.1, 0.2, 0.5 respectively. On the whole, a peak impact force generate in the naked column and the columns safeguarded by the foams with relative densities 0.1, 0.5, while a plateau maximum force maintains a long course for the foam02. For the column safeguarded by the foam01, the peak force arises after a long impacting process due to high compressibility of low density of foam01. On the contrary, for the naked column and the column safeguarded by foam05, the peak forces arise at initial stage of collision.

The peak impact force is the key action resulting in the damage of the column and the truck, so a low peak force is a desired goal for engineering design. The variation of the peak impact forces normalized by that of the naked column with the relative density of the foams is plotted in Fig. 7. It is surprising that the peak impact force descends with the increase of foam density firstly, and ascends later. In other words, there is a minimum peak force corresponding to a certain foam density, which has a great significance for engineering design of safeguard structures to resist impact.

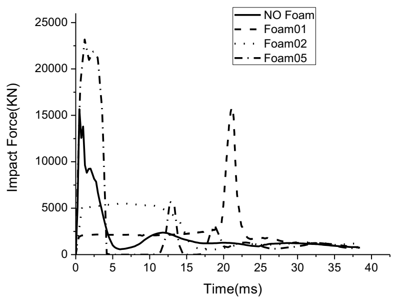

Fig. 6. The resultant impact force-time history

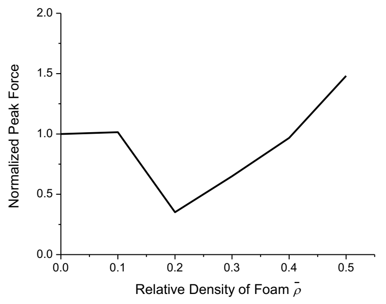

Fig. 7. The variation of the normalized peak forces with relative density of the foams

3.3 ENERGY ABSORPTION CAPACITY

The truck impacting the RC columns at high velocity has high kinetic energy, which needs transform into other type such as internal energy etc. before stasis. How to efficiently absorb the kinetic energy of the truck has an important meaning for the protection of truck and the RC column. Fig. 8 shows the energy absorption characteristic of RC column components of the naked column and the columns safeguarded by the foam01, foam02 and foam05 respectively. For the naked column without safeguard, the most amount of kinetic energy is absorbed by concrete, while the reinforcements absorb little one, which implies that the concrete would deform seriously even damage to a certain extent to absorb kinetic energy. In contrast, for the columns safeguarded by foams, a large part of kinetic energy is absorbed by the foams instead, which means the RC column components would undergo slight deformation and be defended. In addition, the amount of energy absorption of concrete of the columns safeguarded by the foam01, foam02 and foam05 at the time point 50ms is 287KJ, 251KJ, and 475KJ, respectively, which means the column safeguarded by the foam02 generates the smallest deformation and is protected best.

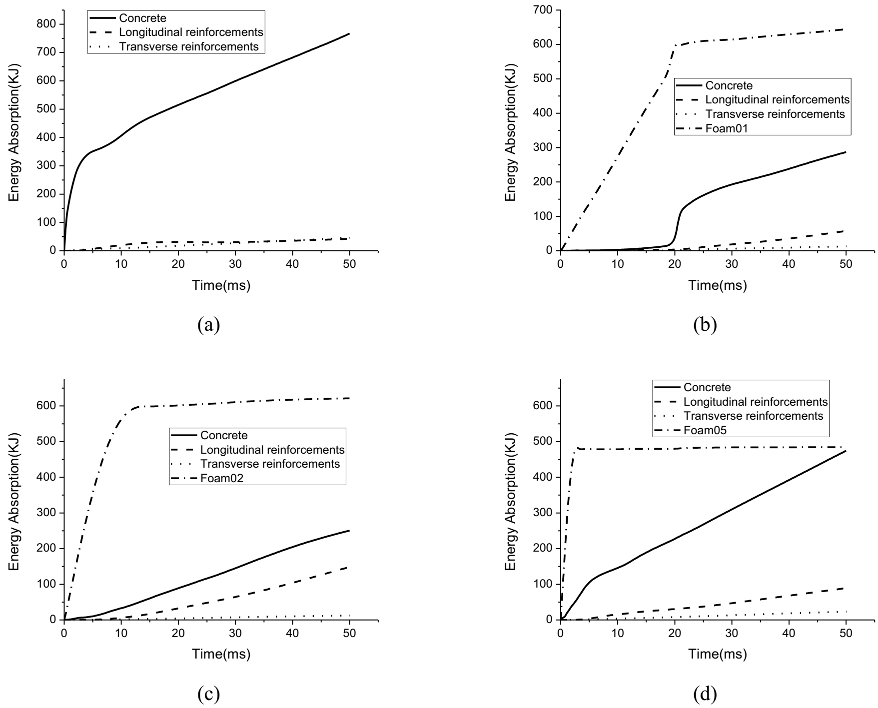

Fig. 8. The energy absorption history of RC columns components: (a) The naked column without safeguard; (b) The safeguarded column by the foam01 with relatively density 0.1; (c) The safeguarded column by the foam02; (d) The safeguarded column by the foam05.

For the convenience of studying the influential characteristic of foam density on the energy absorption, the variation of energy absorption with relative density of the foams is reproduced in Fig. 9. It can be found that the energy absorbing history is roughly divided into two stages. The energy absorption increases with time firstly, and keeps constant after up to a maximum value. At the first stage, the energy absorbing rate of the foams increases with foam density increasing, while the variation of the maximum value of energy absorption demonstrates a contrary tendency, see Fig. 10. In addition, the maximum energy absorption of foam02 is very close to that of foam01, which means the density of foam02 perhaps is the largest density corresponding to the maximum energy absorption. In other words, there appears a highest density corresponding to the maximum energy absorption. Of course, the critical density of foam 0.2 is obtained based on current impact case, and it needs be determined in other impact cases.

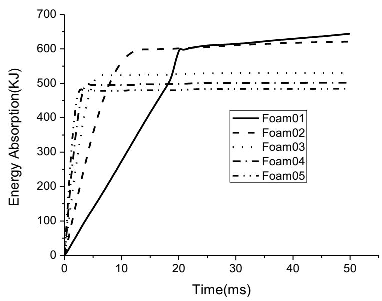

Fig. 9. The variation of energy absorbing performance of the foams with relative density

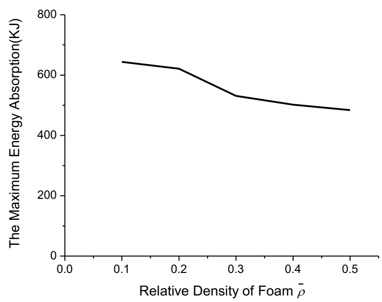

Fig. 10. The variation of the maximum energy absorption of the foams with relative density

4. CONCLUSIONS

When a truck impacts on a RC column at a high velocity, the large impact force generated would damage the truck, hurt the passengers, and destroy the column. It is essential to install some type of safeguard structures to mitigate impact and reduce losses. Foams are typical lightweight materials with excellent energy absorbing performance, which are usually used as safeguard constructions. In the paper, metallic foam safeguarded RC square columns under lateral impact are simulated using ABAQUS code software, where the influence of foam density on the peak impact force and energy absorption is focused on. The simulated results reveals that the truck velocity and the deflection of the columns at the impact position both descend remarkably under buffering of the foams, indicating the foams afford a prominent safeguard to the RC columns. It seems that there is a critical foam density corresponding to the minimum value of the peak impact force, which is of great importance for engineering design to protect the truck, passengers and the column. For the columns safeguarded by foams, the foams absorb the most kinetic energy instead of the column concrete, and less damage would be generated in the columns. It appears that there also exists a critical foam density corresponding to the maximum amount of energy absorption. It is exciting that the two critical foam densities appear to well close to each other, which is of great significance for engineering design of the safeguard constructions to resist impact.

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LIST OF FIGURES AND TABLES:

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