Original Article

Safety assessment of nuclear fuel reprocessing plant under the free drop impact of spent fuel cask and fuel assembly part I: Large-scale model test and finite element model validation

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Article info

Article history:
Received 10 August 2020
Received in revised form 21 January 2021
Accepted 3 February 2021
Available online 12 February 2021

Keywords:
Spent fuel cask
Free drop
Nuclear fuel reprocessing plant
Autoclaved aerated concrete
Numerical simulation

Abstract

This paper aims to evaluate the structural dynamic responses and damage/failure of the nuclear fuel reprocessing plant under the free drop impact of spent fuel cask (SFC) and fuel assembly (FA) during the on-site transportation. At the present Part I of this paper, the large-scale SFC model free drop test and the corresponding numerical simulations are performed. Firstly, a composite target which is composed of the protective structure, i.e., a thin RC plate (representing the inverted U-shaped slab in the loading shaft) and/or an autoclaved aerated concrete (AAC) blocks sacrificial layer, as well as a thick RC plate (representing the bottom slab in the loading shaft) is designed and fabricated. Then, based on the large dropping tower, the free drop test of large-scale SFC model with the mass of 3 t is carried out from the height of 7 m–11 m. It indicates that the bottom slab in the loading shaft could not resist the free drop impact of SFC. The composite protective structure can effectively reduce the damage and vibrations of the bottom slab, and the inverted U-shaped slab could relieve the damage of the AAC blocks layer dramatically. Furthermore, based on the finite element (FE) program LS-DYNA, the corresponding refined numerical simulations are performed. By comparing the experimental and numerical damage and vibration accelerations of the composite structures, the present adopted numerical algorithms, constitutive models and parameters are validated, which will be applied in the further assessment of drop impact effects of full-scale SFC and FA on prototype nuclear fuel reprocessing plant in the next Part II of this paper.

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1. Introduction

Generally, the fuel assembly (FA) removed from nuclear reactors will be stored in the water-filled spent fuel pools for almost ten years [1], since immersing into water can facilitate the radiation shield and heat dissipation of spent nuclear fuel. When the residual heat of the FAs meets the acceptance criteria, they will be stored in spent fuel cask (SFC) temporarily and transported to the remote deep geologic repository until the final decay of radioactivity. The integrity of SFC during the transportation needs to be maintained to protect the population and environment from exposure to the radiation [2,3]. The International Atomic Energy Agency [4], US Nuclear Regulatory Commission [5], American Society of Mechanical Engineers [6], Nuclear and Industrial Safety Agency of the Japanese Government [7], Korea Mest [8] and National Nuclear Safety Administration of China [9] issued relevant regulations for SFC under both normal and accidental transport conditions, e.g., drop, puncture, fire and submersion events [10–13]. At present, the free drop scenario of SFC is mainly concerned.

Extensive experimental and numerical studies have been performed to assess the structural response of SFC under the accidental drop conditions. Saito et al. [14] carried out five drop tests on full-scale SFC casks from drop height of 9.3 m considering the cumulative effects of pre-damage due to 0.3 m drop, and the conformity with the leak-tightness requirements by comparison of the leakage rates before and after full-scale drop test was verified. Then the closure system of the cask was designed based on the measured
strains of the body flange and lids in the tests, and the structural integrity of the cask was demonstrated via the validated numerical simulations. Shirai et al. [15] designed two types of concrete casks, i.e., a reinforced concrete cask and a concrete-filled-steel cask, to perform the horizontal and vertical drop tests from the height of 1 m and 6 m, respectively. The leak-tightness of the concrete casks were confirmed by measuring the leakage rates before and after the drop tests. Besides, the impact loads and strain distributions of the cask and its inner structures during the whole drop process were evaluated numerically. Accordingly, the structural and sealability integrities of the concrete casks were verified. Lo Frano et al. [16,17] also conducted experimental and numerical studies to predict the mechanical performances of a new Italian package drop from the height of 1.2 m. A series of free drop tests of the prototype package was performed, including the vertical drop onto the bottom face of overpack, horizontal drop onto the side face, vertical drop onto the upper face of the lid, and inclined drop onto the upper edge of the overpack lid. Furthermore, the integrity and safety of the transport package were demonstrated according to the dynamic stresses, deformations and accelerations during the horizontal and vertical drop processes by the qualified MARC [18] and ANSYS codes [19], respectively. Kim et al. [20] designed four impact-limiters varying with wood types and grain directions, and further performed a series of horizontal and vertical drop impact simulations of SFC assembled with different impact-limiters based on ABAQUS/Explicit [21]. The post-impact damage of SFC was evaluated as per stress-based and strain-based criteria specified by the American Society of Mechanical Engineers [6], and it was found that the impact limiters could absorb considerable energy and effectively protect the SFC under drop impact.

Considering the huge cost of the full-scale SFC model free drop test, the reduce-scaled model test is an effective alternative, whereas the scaling effect of SFC in the drop impact cases needs to be discussed so that the test data obtained by means of the reduce-scaled models can be extrapolated to the prototype. Wu et al. [22] performed numerical simulations of the vertical drop and 5° oblique drop from 61 cm height of three scaled SFC models (1:1, 1:2.5 and 1:5) with LS-DYNA code [23]. The results showed that the maximum acceleration decreased with increasing the scaling coefficient, thus the small-scaled test is nearly impossible to predict the responses of the prototype test. Aquaro et al. [24] carried out the 9 m free drop test of three scaled spent fuel cask models (1:2, 1:6 and 1:9) assembled with the corresponding scaled shock absorber models, and performed the similitude analysis of the scale model and the full-scale prototype. Besides, the numerical simulations of five shock absorber models (1:1, 1:2, 1:6, 1:9 and 1:12) were conducted by using MSC-MARC code [18]. It was found that the small discrepancies of the post-impact displacements, accelerations and impact durations were obtained by using large-scale models (1:2 and 1:6), while the small-scale models (1:12) did not give the reliable results. Hence, to obtain more accurate results, the large-scale model of SFC should be adopted for the free drop issues.

The above-mentioned existing studies are mainly concerning the integrity, safety, leak-tightness of the SFC structure under the accidental drop, as well as the applicability of the scaling law of SFC model for the drop test. In fact, for the accidental drop of SFC in the nuclear fuel reprocessing plant shown in Fig. 1(a), the structural dynamic responses and damage/failure of the slabs that might be impacted by the free drop of SFC also need to be concerned, considering that the free drop of SFC might cause severe damage and vibrations to the underneath slab, and the precision instruments placed on the slabs might malfunction due to the severe vibrations. Apart from that, the stored FAs might also be affected by the vibrations result from the impact of drop FA during hoisting in spent fuel pool, and the impact would also induce damage to the bottom slab in the pool, as shown in Fig. 1(b). Therefore, the structural responses of the slabs which might be impacted by the free drop of SFC and FA need to be evaluated, and the efficient protective measures need to be proposed in the free drop scenarios of SFC. However, the related studies regarding the safety assessment and protective design of nuclear fuel reprocessing plant under the free drop of SFC are relatively limited. In order to fill the related research gaps, this paper intends to study the dynamic responses and damage of the slabs that might be impacted by the free drop of SFC and FA, and propose an effective protective measure to relieve the damage and vibrations of the impacted slabs.

Autoclaved aerated concrete (AAC) is a kind of precast concrete with favorable characteristics in terms of lightweight, high fire resistance, cost-saving [25,26], and excellent energy absorption capacity [27–29]. Hence, AAC blocks could be utilized as the sacrificial layer to protect the slabs inside the nuclear fuel reprocessing plant under the drop impact of SFC. Nevertheless, AAC blocks couldn’t be directly impacted by SFC since the high permeability [30] of which might lead to the water within the loading shaft permeate through the bottom slab, as shown in Fig. 1(a). Therefore, in this paper, the composite protective structure including an inverted U-shaped slab and an AAC blocks layer is proposed and arranged above the bottom slab to resist the accidental drop impact of SFC, where the inverted U-shaped slab could protect the AAC blocks layer and provide support for the waterproof steel liner. At the present Part I, the free drop test of large-scale SFC model with the mass of 3 t is firstly carried out from the heights of 7 m–11 m based on the large dropping tower, in which three typical targets including the thick RC plate (representing the bottom slab in the loading shaft), “AAC blocks layer + thick RC plate”, and “thin RC plate (representing the inverted U-shaped slab in the loading shaft) + AAC blocks layer + thick RC plate” are considered. Then, based on the FE program LS-DYNA [23], the FE model of the free drop test is established and the corresponding numerical simulations are performed. Furthermore, the predicted damage and vibration accelerations of the composite structures are compared with the test data. The validated numerical algorithms, constitutive models and parameters will be applied to the refined numerical simulations of drop impact effects of full-scale SFC and FA on prototype nuclear fuel reprocessing plant in the next Part II of this paper.

2. Free drop test

2.1. Specimens

The schematic diagram of the drop test of SFC is shown in Fig. 2, and the dimensions and reinforcement details of the specimens are shown in Fig. 3. Based on the existing studies, only the large-scale models could provide reliable results in the drop impact cases [22,24]. At present, the SFC model with size scale factor of 1/3 is adopted and the mass of which is 3 t. Besides, since not the deformation of the SFC structure but the impact effect of the SFC is concerned, a steel cask filled with concrete was fabricated to substitute the actual SFC. The dimensions of the SFC model is shown in Fig. 3(a), and two hooks are welded on the top surface of the model considering the lifting requirement.

Similarly, a 1/3 scaled RC plate (labelled as thin RC plate) is adopted to substitute the inverted U-shaped slab in the loading shaft for the fabrication convenience and cost reduction. Besides, the constraint of the inverted U-shaped slab on the AAC blocks layer is realized by the steel jacketing. Although the constraint of the AAC blocks layer in the test is weaker than that in the actual plant, the drop test could reveal structural dynamic responses and damage/failure of the targets, and provide the benchmark for the
Fig. 1. On-site hoist and transportation process (a) SFC (b) FA.

Fig. 2. Schematic diagram of test (a) photograph (b) overview.

Fig. 3. Dimensions and reinforcement details (a) SFC (b) thin RC plate and thick RC plate (c) steel jacketing (d) AAC blocks layer (unit: mm).
further numerical simulations. The bottom slab in the loading shaft is scaled down to a 1/3 scaled RC plate (labelled as thick RC plate). The compressive strengths of concrete is 40 MPa, and the dimensions of the thin RC plate and thick RC plate are 2400 mm × 2400 mm × 200 mm and 2400 mm × 2400 mm × 400 mm, respectively. The corresponding reinforcement detailing are identical and shown in Fig. 3(b). Several hooks are pre-embedded in the thin RC plate and welded on the upper edges of the symmetrical sides of steel jacketing to fulfill the lifting requirement, as shown in Fig. 3(b) and (c). The dimension of the AAC block inside of the steel jacketing is 600 mm × 200 mm × 100 mm, and the density of the AAC block is 771 kg/m³. The AAC blocks layer with the height of 1500 mm is stacked by 15 layers of AAC blocks, and the layout size of the AAC blocks is 2400 mm × 2400 mm, as illustrated in Fig. 3(d).

2.2. Setup

As shown in Fig. 4, the drop test was performed based on the large dropping tower with the maximal drop height of 60 m and weight of 4 t. To ensure the free drop of SFC without any movement or lateral inclination, the release of SFC is realized via the detonation of the explosive bolt attached to the top of the dropping tower structure. The test is conducted by tying the hooks reserved on the top surface of the SFC model to the auxiliary strings and lifting the SFC model to the predetermined height through the hydraulic lifting device. The other function of the auxiliary strings is to prevent the unexpected impact of the SFC model to the test facilities. After adjusting the SFC model to vertical drop orientation, the SFC model could be released once the explosive bolt is detonated. As for the configuration of the targets, the thick RC plate is simply supported by two steel plates considering the actual boundary condition shown in Fig. 1(a), the AAC blocks layer is stacked upon the thick RC plate and constrained by the steel jacketing, the thin RC plate is placed at the top. After each drop test, the damage of the targets is inspected and measured, and the damaged thin RC slab and the crushed blocks are replaced with new ones.

To monitor the vibration responses of the thick RC plate, two CA-YD-125A piezoelectric accelerometers with measuring range from 0 to 20000 g are applied, one of which (A1) is attached to the rear surface center of the thick RC plate, the other one (A2) is attached 200 mm away from A1. The accelerometers are connected to the data acquisition system, and the sampling frequency is 100 kHz. Additionally, a high-speed camera is used to record the orientation and impact process of the SFC model at frame rate of 2000 fps. The captured images are imported to the Photon FASTCAM Analysis software, which can provide simple motion analysis for the tracking markets placed on the images, and obtain the quantitative data, e.g., the velocity.

The details of the free drop test are given in Table 1. Test 1 is served as a control test in which only the thick RC plate is arranged without the composite protective structure. Besides, to determine the energy absorption capacity of the AAC blocks layer under the free drop impact of SFC, the AAC blocks layer is arranged above the thick RC plate in Test 2. In Test 3 to Test 5, the composite protective structure consisted of a thin RC plate and an AAC blocks layer is arranged above the thick RC plate, and the effects of the drop height of SFC model on the damage and failure of the composite protective structure and the thick RC plate are examined. It should be pointed out that, the drop height in Test 1 is the distance from the bottom surface of SFC to the top surface of the thick RC plate, and the drop heights in Test 2 to Test 5 are determined as the distance from the bottom surface of SFC to the top surface of the composite protective structure.

2.3. Results and discussions

2.3.1. Impact process of SFC

The impact process of SFC recorded by the high-speed camera is shown in Fig. 5. It is clearly observed that, at the initial instant of the impact, i.e., 0 ms, the SFC models are all perpendicular to the target. That is to say, the normal impact is realized in the present test. For Test 1, the horizontal tensile crack appears on the side surface in the direction perpendicular to the steel plate supports at 9 ms after the thick RC plate is impacted, then the tensile crack propagates progressively and converges with the vertical flexural cracks close to the inner edges of the steel plate supports, eventually forming the scabbing of concrete on the rear surface of the thick RC plate at 21.5 ms, as shown in Fig. 5(a). For Test 2, the lower part of the SFC model with the height of 250 mm totally penetrates the AAC blocks layer at 24 ms, and the entire impact process of the SFC model lasts for 76.5 ms, as shown in Fig. 5(b). Concerning Tests 3–5, the duration of the impact process of the SFC model increases with the elevation of the free drop height, which are 8.5 ms, 13 ms and 19.5 ms, respectively, as shown in Fig. 5(c–e).

The instantaneous velocities of SFC in the test are obtained through the high-speed camera and the Photon FASTCAM Analysis software, as shown in Fig. 6. The initial velocities of the SFC model in Test 1–5 are 11.460 m/s, 11.483 m/s, 11.721 m/s, 13.437 m/s, 14.562 m/s, respectively. Thus, the initial velocities of the SFC model in Test 1–5 are close to the predetermined values given in Table 1. It should be noted that there is a deviation between the calculated and test velocity due to the error in tracking the motion of marker by Photon FASTCAM Analysis software.

2.3.2. Target damage

The damage of the thick RC plate under the free drop impact of the SFC model is presented in Table 2, including the cratering on the front surface, the scabbing on the rear surface and the cracks on the side surface. The post-impact damage of the AAC blocks layer is presented in Table 3, including the cratering in the impact region and the surrounding cracks. Besides, the damage of the thin RC plate is presented in Table 4, including the cratering on the front surface and shear plugging on the rear surface. The abbreviations CD, PD, SD, SH, SPD, SPM, F and R in Tables 2–4 denote the cratering diameter, penetration depth, scabbing diameter, scabbing height, shear plugging diameter, shear plugging height, the front surface and rear surface, respectively.
From Tables 2–4, it indicates that, (i) in Test 1, the cratering diameter and penetration depth of the thick RC plate are 660 mm and 85 mm, respectively. The rear scabbing dimension of the thick RC plate is about 2400 mm × 810 mm × 110 mm. The severe damage of the thick RC plate in Test 1 indicates that the bottom slab in the loading shaft could not withstand the free drop impact of SFC without any protective measures; (ii) the thick RC plate in Test 2 is effectively protected by the AAC blocks layer, and only slight vertical cracks appear in the tension zone on the side surface of the thick RC plate and develop towards the compression zone. The comparison of the damage of thick RC plate in Test 1 and Test 2 demonstrates the prominent energy absorption capacity of AAC. Furthermore, as the directly impacted target, the damage of the AAC blocks layer is the most serious attributed to its low strength, the cratering diameter and penetration depth of which are 940 mm and 435 mm, respectively. Nonetheless, the penetration depth of the AAC blocks layer is much less than its construction thickness (1500 mm), implying a great safety redundancy. Hence, in the practical design, the thickness of AAC blocks layer needs to be optimized; (iii) in Test 3 to Test 5, the cratering diameter and penetration depth of the thin RC plate are ranged from 650 mm to 700 mm and 25 mm–110 mm, respectively. Furthermore, the height and diameter of shear plugging of the thin RC plate are ranged from 30 mm to 120 mm and 770 mm–870 mm, respectively. It indicates that the damage of the thin RC plate would increase with the rising of the drop height of SFC, i.e., the impact kinetic energy of SFC. Concerning the damage of the AAC blocks layer, due to the presence of the top thin RC plate, the blocks in the impact region show a shallow cratering in conjunction with annular cracks develop around the impact region. It indicates that the top RC plate could relieve the damage of the AAC blocks layer dramatically. Besides, some annular cracks propagate to the corners of the AAC blocks layer in Test 5, implying that the damage of the AAC blocks layer would increase with the rising of the drop height. Concerning the damage of the thick RC plate, only several cracks appear on the side face, demonstrating that the composite protective structure can effectively protect the bottom slab in the loading shaft under the impact of SFC without exhibiting serious damage.

2.3.3. Vibration responses

The original vibration accelerations of the thick RC plate recorded by the accelerometers A1 and A2 are illustrated in Fig. 7. The raw data contains free vibration and resonance of the thick RC plate in different modes with relatively high frequencies as well as measurement noise. To eliminate the noise and other modes of vibration that are not of interest, the fast Fourier transform was applied to the raw data to identify the suitable cutoff frequency. The accelerations recorded by the accelerometer A1 in Test 1–5 are taken as examples to perform the fast Fourier transform, and the frequency spectrums of the accelerations are illustrated in Fig. 8. It is evident that the high Fourier amplitudes are concentrated below 1000 Hz. Therefore, a 7th order low-pass Butterworth filter with 1000 Hz cutoff frequency was applied to filter the raw data, as shown in Fig. 7. It is seen that the peak accelerations in Test 2 to Test 5 are far lower than those in Test 1, i.e., the vibrations of the thick RC plate with the composite protective structure are significantly lower than those without composite protective structure. It demonstrates that the composite protective structure can dramatically reduce the vibration response of the bottom slab in the loading shaft. The accelerations of the thick RC plate among Test 1–5 are quite different from each other, since the configuration of the targets and the drop height of the SFC are various, and multiple reflections of shock waves occur at the interface of different layers. Furthermore, the peak accelerations of the thick RC plate decrease as the drop height of SFC increases in Test 3–5. It might be attributed to the energy dissipation as a result of target cracking. Specifically, a large number of cracks appear in the AAC blocks under the impact of SFC in Test 2, and the cracks in the thin RC plate and the AAC blocks increase extensively with the rising of the drop height of SFC in Test 3–5. As these cracks dissipate amounts of impact energy, the vibrations of the thick RC plate in Test 2, Test 4 and Test 5 are weakened consequently.

3. Numerical simulations

3.1. FE model

To determine the numerical simulation algorithms, constitutive models and parameters for further investigating the structural response of the prototype nuclear fuel reprocessing plant subjected to the free drop impact of full-scale SFC and FA, the numerical simulations of the present 1/3 scaled model free drop test are conducted by adopting the FE program LS-DYNA [23].

Fig. 9 illustrates the details of the established FE models and the corresponding element types for each component. It should be emphasized that since the damage of SFC is not concerned in this paper, the solid model with homogeneous material is used for simplification, instead of accurately simulating the spent fuel inside. The bottom surfaces of steel plate supports are fixed, and the side surfaces of the AAC blocks layer are fixed in the normal direction to simulate the constraint of steel jacketing. The interaction between rebar and concrete is realized by the option *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE. The contact behavior between the SFC model and the impacted targets, in which the SFC model and the impacted targets are set as slave surface and master surface, respectively. This contact algorithm provides a way of treating interaction between surfaces of the elements, and the interaction occurs when the slave segment contacts or moves very near the master segment. The self-contact for the impacted targets is implemented by the option *CONTACT_AUTOMATIC_SINGLE_SURFACE, this algorithm can detect all the contacts occurring in the specified element groups. The initial impact velocity obtained by the test is applied to the SFC model as an initial condition, which is realized by the option *INITIAL VELOCITY GENERATION. This option can define initial velocities for rotating and translating bodies.
Fig. 5. Experimental impact process of SFC in (a) Test 1 (b) Test 2 (c) Test 3 (d) Test 4 (e) Test 5.
To guarantee the requirement of calculation precision and reduce the computing cost, an appropriate element size should be adopted in the mesh division of the targets, especially in the impact region. Test 3 is taken as example for the mesh convergence analyses. A total of five different element size, i.e., 15 mm, 20 mm, 25 mm, 30 mm and 35 mm, are adopted in the meshing of the impact region of the targets, and the element erosion is not considered in the mesh convergence analyses. The damage of the thin RC plate with five different element size under the free drop impact of SFC is shown in Fig. 10, in which the abbreviations F and R denote the front and rear surfaces, respectively. Moreover, the corresponding impact force and the velocity-time histories of SFC are illustrated in Fig. 11. It is evident that the predicted velocity-time histories of SFC from the five mesh sizes are similar, while the predicted damage on the front and rear surface of the thin RC plate as well as the peak impact force of SFC would be larger when the element size is coarser. In general, the simulation results obtained from the model with the element size of 20 mm are close to those obtained from the model with the element size of 15 mm, whereas the computational cost of the latter is twice that of the former. Considering both accuracy and computational efficiency, the element size is set as 20 mm with a radial distance of 400 mm from the impact center, and the element size is enlarged to 40 mm for the remaining part.

| No. | Test | Simulations |
|-----|------|-------------|
| Test 1 | ![Image](image1.png) |
| Test 2 | ![Image](image2.png) |
| Test 3 | ![Image](image3.png) |
| Test 4 | ![Image](image4.png) |
| Test 5 | ![Image](image5.png) |
The concrete is modeled with the MAT_CSCM_CONCRETE model (MAT#159 in LS-DYNA [23]), which is a cap model with a smooth interaction between the shear yield surface and hardening cap. It can effectively describe the material properties of concrete, such as the damage-based softening and modulus reduction, shear dilation, shear compaction, confinement effect and strain rate effects. Softening behaviors are controlled by the damage parameter \( d \). As damage accumulates, \( d \) increases from an initial value of 0, towards a maximum value of 1, and an element loses all strength and stiffness as \( d \) tends to 1.

\[
d(t) = \frac{0.999}{D} \left[ \frac{1 + D}{1 + D \exp^{-C(t_d - t_0)}} - 1 \right] \quad (1a)
\]

\[
d(c) = \frac{d_{\text{max}}}{B} \left[ \frac{1 + B}{1 + B \exp^{-H(t_c - t_{c0})}} - 1 \right] \quad (1b)
\]

where \( t_d \) and \( t_c \) are the tensile and compressive energy-type terms, respectively; \( t_0 \) and \( t_{c0} \) are the tensile and compressive damage thresholds, respectively; \( d_{\text{max}} \) is the maximum damage level that can be attained. \( A \) and \( B \) or \( C \) and \( D \) are the parameters that determine the shape of the softening curve plotted as stress-displacement or stress-strain.

MAT_BRITTLE_DAMAGE model (MAT#96 in LS-DYNA [23]) is selected to describe the AAC blocks. It is an anisotropic brittle damage model which admits the progressive degradation of tensile and shear strengths across smeared cracks that are initiated under tensile loadings. There are three damage surfaces in this model to obtain the damage degradations, which are given by

\[
f_1 = S_1 : \sigma - f_n + k_n (1 - \exp[-Ha]) \leq 0 \quad (2a)
\]

\[
f_2 = |S_2 : \sigma - f_s + k_s (1 - \exp[-Ha])| \leq 0 \quad (2b)
\]

\[
f_3 = |S_3 : \sigma - f_s + k_s (1 - \exp[-Ha])| \leq 0 \quad (2c)
\]

where \( S_1 = n \otimes n S_2 = (n \otimes m + m \otimes n)/2S_3 = (n \otimes l + l \otimes n)/2 \), in which \( n, m \) and \( l \) are unit vectors representing three directions in an orthogonal coordinate system, respectively; \( \sigma \) is the stress tensor; \( f_n \) and \( f_s \) are the critical tensile and shear traction across the smeared crack plane, respectively; \( k_n \) and \( k_s \) are coupling constants; \( H \) is the softening modulus; \( a \) is an internal variable.

MAT_SIMPLIFIED_JOHNSON_COOK model (MAT#98 in LS-DYNA [23]) is employed as the material model of SFC, which is one of the most commonly used material models for metallic materials. Compared with the MAT_JOHNSON_COOK model (MAT#15 in LS-DYNA [23]), this simplified model is 50% faster attributed to the simplifications in regard to thermal softening and damage. The simplified flow stress is expressed as

---

**Table 3**

| No. | Test | Simulations |
|-----|------|-------------|
| Test 2 | ![Image] | ![Image] |
| Test 3 | ![Image] | ![Image] |
| Test 4 | ![Image] | ![Image] |
| Test 5 | ![Image] | ![Image] |

**Table 4**

| No. | Test | Simulations |
|-----|------|-------------|
| Test 3 | ![Image] | ![Image] |
| Test 4 | ![Image] | ![Image] |
| Test 5 | ![Image] | ![Image] |
$s_y = (A + B \varepsilon_p^n) (1 + c \ln \varepsilon^*)$  \hfill (3)

where $s_y$ is the effective stress; $A$ is the yield strength; $B$ is the hardening modulus; $\varepsilon_p$ is the effective plastic strain; $n$ is the hardening coefficient; $c$ is the strain rate sensitivity coefficient; $\varepsilon^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the effective strain rate for $\dot{\varepsilon}_0 = 1 s^{-1}$.

The material constitutive model of MAT_PLASTIC_KINEMATIC model [34] (MAT#3 in LS-DYNA [23]) is applied for modeling the rebars embedded in the concrete plate with considering the strain rate effects. Besides, MAT_PLASTIC_KINEMATIC model is also adopted to model the steel plate supports. The dynamic yield strength of steel is taken into consideration by the Cowper-Symonds formula for uniaxial tension or compression as [35].

$$\frac{s_d}{s_s} = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/P}$$  \hfill (4)

where $s_d$ is the dynamic yield strength; $s_s$ is the static yield strength; $\dot{\varepsilon}$ is the strain-rate; $C$ and $P$ are constants of the Cowper-Symonds relation.

The corresponding main material parameters of above adopted models are presented in Table 5. Aiming to exactly predict the damage of the thick RC plate and the composite protective structure under the free drop impact of SFC, the element erosion technique is adopted for MAT#159 and MAT#96 via the keyword MAT_ADD_EROSION [36–39]. The erosion algorithm is adopted to describe the physical fracture and failure process of the Lagrange material as well as handle the large distortion problem. At present, the concrete and AAC blocks elements will be deleted immediately when the damage exceeds 0.99 and the maximum principal strains of MAT#159 and MAT#96 arise to the prescribed values. By trial and error, the values of 0.08 and 0.085 are adopted for MAT#159 and MAT#96, respectively.

### 3.2. Comparisons

#### 3.2.1. Impact process

The typical instantaneous impact instants obtained by the numerical simulations of the present impact test are illustrated in Fig. 12. It can be found that, (i) for Test 1, several concrete elements in the mid-span area of side surface of the thick RC plate are deleted at 9 ms, which is in consistent with the appearance time instant of the horizontal tensile crack of the thick RC plate shown in Fig. 5(a). Then more concrete elements are deleted at 14 ms, indicating a larger crack width, which is also in good agreement with the

![Fig. 7. Raw and filtered accelerations (a) Test 1 (b) Test 2 (c) Test 3 (d) Test 4 (e) Test 5.](image)

![Fig. 8. Frequency spectrums of the accelerations.](image)
development of the horizontal crack observed in the test. Finally, the SFC stop the downward impact on the thick RC plate at 29 ms in the simulation, which is longer than the terminate impact instant in the test, i.e., 21.5 ms, and the rupture of the rebars in the impact region of the thick RC plate is observed in the simulation; (ii) for Test 2, the bottom part of SFC with the height of 250 mm totally
penetrates the AAC blocks layer at 24 ms, which agrees well with the observation in Fig. 5(b). Besides, the impact of SFC in the simulation of Test 2 lasts for 78.5 ms, which is also basically the same as the test results, i.e., 76.5 ms; (iii) for Test 3 to Test 5, the impacts of SFC in the simulations last for 11.5 ms, 14.5 ms and 27.5 ms, while the corresponding experimental terminate impact instants in Test 3, Test 4 and Test 5 are 8.5 ms, 13 ms and 17 ms, as shown in Fig. 5(c–e), it indicates that the duration of impact (from the instant of the contact between SFC and targets to the impact termination) in the simulations are longer than those in the test, the deviation is particularly significant for Test 5. Besides, the rupture of the rebars in the impact region of the thin RC plate is observed in the simulations, which is especially obvious in the simulation for Test 5.

In summary, the impact processes of SFC in the simulations are in good agreement with those in the test, except for the deviations between the experimental and numerical duration of impact for Test 1 and Test 5. This may be attributed to the difference in the experimental and numerical duration of impact for in good agreement with those in the test, except for the deviations as the effective plastic strain tends to 1. It is evident that the maximum acceleration amplitude of the thick RC plate appears once the SFC contacts the thick RC plate. However, the second peak accelerations obtained by Test 5 and the simulated values for Test 2–5 are larger than the first peak accelerations. It might be attributed to the multiple reflections of shock waves at the interface of different layers. Besides, the appearance and development of cracks also make the propagation of vibrations more complicated. Hence, larger acceleration amplitude appear on the rear face of the thick RC plate after the instant of contact. Despite the discrepancy of the accelerations in the test and simulations, the simulated peak accelerations are of the same order as the corresponding experimental results. Therefore, the numerically simulated accelerations are reasonable and acceptable, and the proposed modeling methodology is suitable for examining the vibration responses of the structures in nuclear fuel reprocessing plants under the free drop impact of SFC with or without the composite protective structure.

3.2.3. Vibration acceleration

The accelerations of the thick RC plate obtained via the simulations are filtered by a 7th order low-pass Butterworth filter with 1000 Hz cutoff frequency, and the filtered numerical and experimental accelerations are compared as shown in Fig. 13. It is clear that the maximum acceleration amplitude of the thick RC plate appears once the SFC contacts the thick RC plate. However, the second peak accelerations obtained by Test 5 and the simulated values for Test 2–5 are larger than the first peak accelerations. It might be attributed to the multiple reflections of shock waves at the interface of different layers. Besides, the appearance and development of cracks also make the propagation of vibrations more complicated. Hence, larger acceleration amplitude appear on the rear face of the thick RC plate after the instant of contact. Despite the discrepancy of the accelerations in the test and simulations, the simulated peak accelerations are of the same order as the corresponding experimental results. Therefore, the numerically simulated accelerations are reasonable and acceptable, and the proposed modeling methodology is suitable for examining the vibration responses of the structures in nuclear fuel reprocessing plants under the free drop impact of SFC with or without the composite protective structure.

3.2.2. Dynamic damage

The numerically predicted damage of the composite protective structure and the thick RC plate are presented in Table 2 to Table 4, in which the damage of the thick RC plate is evaluated through the effective plastic strain, i.e., an element is undamaged when the effective plastic strain equals to 0, and loses all strength and stiffness as the effective plastic strain tends to 1. It is evident that the simulation results show a small discrepancy with the test results, including the cratering on the front surface of the top thin RC plate, the middle AAC blocks layer and the bottom thick RC plate, the shear plugging on the rear surface of the thin RC plate, as well as the scabbing on the rear surface of the thick RC plate. The effective plastic strain contours of the thick RC plate in the simulations for Test 2 to Test 5 are almost the same, and the implied damage is much smaller than that in the simulation for Test 1. It is consistent with the damage level of the thick RC plate in the test. Additionally, in the simulations for Test 2 to Test 5, the effective plastic strains of the elements on the side surface of the thick RC plate arise to 0.99, indicating the damage of the concrete. It is also consistent with the horizontal tensile cracks observed in the test. In summary, the damage in the simulations is consistent with the test, and the deviation between the test data and simulation results might be attributed to the measuring deviations.

4. Conclusions

Aims to evaluate the structural dynamic responses and damage/failure of the nuclear fuel reprocessing plant under the free drop impact of SFC and FA during the on-site transportation, at the present Part I of this paper, the composite protective structure including an inverted U-shaped slab and an AAC blocks layer is proposed and arranged above the bottom slab in the loading shaft to resist the accidental drop impact of the SFC. Based on the 1/3 scaled SFC model free drop test and the corresponding numerical simulations, the impact resistance of the composite target is evaluated. The following conclusions can consequently be drawn: (i) the bottom slab in the loading shaft could not resist the free drop impact of SFC without arranging any protective measures; (ii) AAC possesses great energy absorption capacity and can effectively reduce the damage of the bottom slab, and the inverted U-shaped slab could relieve the damage of the AAC blocks layer significantly; (iii) the proposed composite protective structure can dramatically
reduce the vibration response of the bottom slab in the loading shaft; (iv) the simulated results show a good coincidence with the experimental data, despite the discrepancy of the accelerations in numerical simulations versus experimental test. The present adopted numerical algorithm, constitutive model and parameters are validated, which will be applied to the refined numerical simulations of full-scale drop impact effects of SFC and FA on prototype nuclear fuel reprocessing plant in the next Part II of this paper.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The project was supported by the National Natural Science Foundation of China (51878507).

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