- Technical Paper -

NUMERICAL SIMULATION OF DYNAMIC PUNCHING TEST OF POLYUREA USING APPLIED ELEMENT METHOD

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ABSTRACT

In this study, dynamic punching tests of polyurea with different polyurea thickness were investigated using Applied Element Method (AEM) simulation. The simulation results were verified based on the experimental results. It was found in this study that a 3mm and a 10mm thick polyurea with 500mm x 500mm area could not withstand 758J and 3,983J impact energy, respectively. However, a 5mm thick polyurea could withstand 758J impact energy. Effectiveness of the polyurea sheet depended on impact energy, polyurea thickness, bond strength, and material properties of polyurea and primer.

Keywords: polyurea, dynamic loading, punching test, Applied Element Method.

1. INTRODUCTION

Brittle fracture of prestressing tendon in PC bridge may result in the protrusion of the tendon from the bridge, causing a serious public safety hazard from ejecting bars or falling concrete [1-3]. In 2018, actual rupture of a vertical PC bar in a bridge was investigated by the authors. It was concluded that the rupture of the bar was brittle and initiated from corrosion pits which were caused by cyclic drying and wetting due to the ingress of rainy water [4-5].

Protection measures against the eruption of PC bar tendons are necessary, so that the damage to third party is avoided [6]. Steel plate and FRP sheet were used on the surface of concrete as a countermeasure against the protrusion of PC bars [7]. However, using steel plate and aramid fiber as a countermeasure on the bottom side of PC bridges takes a longer construction time which is not recommended for Metropolitan Expressway MEX as the structures are located in city areas. This paper investigates the effectiveness of a polyurea material against impact resistance and concrete spalling.

A polyurea coating is the result of a one-step reaction between an isocyanate component and a resin blend component [8]. Polyurea is widely used as a protective coating material for structures subjected to impulsive loads [8-12]. Polyurea spray coating technology combines fast curing, even at very low temperatures, and water insensitivity with exceptional mechanical properties, chemical resistance and durability [8]. Their mechanical behavior at a very high strain rate is of particular interest [12-13], because the protrusion of PC bars will generate very high strain rate in concrete and polyurea. Spraying polyurea might be applied to prevent protrusion and spalling with less construction time. FRP sheet cannot be applied well when the surface is not smooth [14], but polyurea can be applied to such surface.

A finite-element analyses using ABAQUS/Explicit about a mechanism behind the protective benefit offered by the polyurea coating were carried out using a transient non-linear dynamics finite-element approach [11,15,16]. The nonlinear finite element (FE) code, LS-DYNA was used to simulate the characteristics and behavior of the polyurea coating [17]. However, in this study, a numerical model of punching test of polyurea is developed in AEM due to its advantages of simulating structural progressive collapse [18]. Experimental results are used for validation of numerical investigations.

In this study, punching tests for polyurea with thickness of 3mm, 5mm and 10mm under different impact loads were investigated. The results obtained are used to assess the extent of energy absorption and to identify the mode of failure of the polyurea as a function of the imposed impact conditions.

Therefore, the objective of the present study is to numerically investigate the effects of polyurea coating on impact resistance and on preventing concrete spalling. The numerical simulation tool developed in this study will be utilized in the future for evaluating the effectiveness of polyurea against rupture and protrusion of PC bar tendon and concrete spalling in PC bridges.

2. EXPERIMENTAL PROGRAMS

2.1 Materials

(1) Polyurea

Mechanical properties of aromatic polyurea are shown in Table 1. Tensile strength and elongation of the polyurea were obtained from experimental investigation based on JIS K 6251. Two kinds of liquids were mixed

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by collision using a spray gun, forming coating of 3mm, 5mm and 10mm thickness.

Table 1 Mechanical properties of polyurea

Properties	Values
Tensile strength (MPa)	22
Elongation (%)	300
Durometer hardness (D type)	51
Tear Resistance (N/mm)	90
Volume resistivity (Ω.cm)	10^7

(2) Adhesive

For dry concrete, applying primers can improve adhesion results [8]. The adhesive strength of the polyurea coating with a primer was experimentally investigated by pull-off adhesion test on dry concrete and it was 1.32MPa. The pull-off adhesion test was based on JIS A6909 6.10 standard. The concrete surface was smoothened by a sandpaper before applying the primer. During this test, a concrete cohesive failure was observed due to poor-quality surface concrete despite adhesive failure was expected. However, according to Japanese highway company guidelines, the specified value for the adhesive strength of spalling prevention material is more than 1.5MPa [14].

(3) Concrete

A prefabricated concrete product based on JIS A 5372 was used.

2.2 Loading Method

A numerical simulation of rupture and protrusion of PC bar was conducted by the authors using AEM [4]. The prestress force after prestress loss was 591kN ($0.6P_u$). The PC bar tendon used was a 5.0m standard steel bar: SBPR930/1180 (class B2 in JIS). PC bar rupture length was 4.5m measured from the PC bar head. Strain energy of the PC bar was 4,408J [4].

In this study, the impact energies were decided by taking 17% (758J) and 90% (3,983J) of the strain energy of the 4.5m PC bar mentioned above. The experiments were carried out using a drop weight test instrument as shown in Fig 1. Three types of punching tests were conducted with different impact loading and with different polyurea thickness as shown in Table 2. The kinetic energy of the drop weight at impact in Case 1 and Case 2 was 758J which represents 17% of the strain energy of the PC bar, while the impact energy in Case 3 was 3,983J which represents 90% of the strain energy of the PC bar.

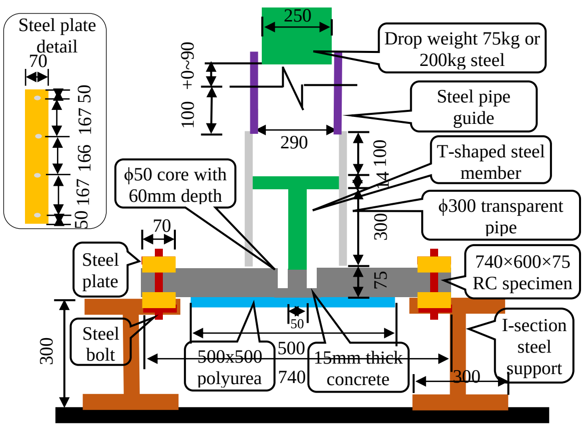


Fig.1 Drop weight test

Table 2 Types of polyurea punching shear test

Cases	Thickness of polyurea (mm)	Drop weight (kg)	Drop height (m)	Impact energy (J)
Case 1	3	75	1	758
Case 2	5	75	1	758
Case 3	10	200	2	3,983

2.3 Testing Procedure

A reinforced concrete specimen, 740mm × 600mm × 75mm, with coring at the center of the specimen was provided. The core had inner diameter of 50mm and outer diameter of 55mm and 60mm depth. 15mm thick concrete remained below the core. The bottom surface of the concrete specimen was smoothened by a sandpaper before applying a primer. A primer was used to attach a 500mm × 500mm polyurea on the bottom surface of the concrete specimen. The concrete specimen was fixed with I-section steel support using steel plates and bolts as shown in Fig 1. A T-shaped steel member was attached to the center of the specimen to transfer the impact load to the concrete and to the polyurea. Deformation and failure processes of the polyurea under high-speed punching were recorded with the aid of a high-speed camera.

3. AEM SIMULATION OF PUNCHING TEST OF POLYUREA

3.1 Simulation with Applied Element Method (AEM)

Applied Element Method (AEM) is based on dividing the structural members into virtual elements connected through springs. Each spring entirely represents the stresses, strains, deformations, and failure of a certain portion of the structure. AEM allows to perform static and dynamic analysis [18-20]. In this study, a non-linear structural analysis software `Extreme Loading for Structure (ELS)` based on AEM was used [21].

3.2 AEM Simulation Modeling

AEM numerical simulation was conducted for the drop weight test explained in Fig. 1. The details of the modeling of the punching test are shown in Fig. 2. The reinforced concrete specimen was fixed at its edges at the bottom as shown in Fig. 2(b) (marked with yellow color). The drop weight was free in all degrees of freedom as it falls under gravity. The T-shaped steel member was free to move only in z-direction.

In the analysis, two stages of loading were provided. The first one was static to account for boundary conditions and self-weight of polyurea, concrete and steel, while the second one was dynamic to simulate the drop weight and its impact to concrete and polyurea. The initial condition of the weight drop stage was zero initial velocity. In the AEM simulation, a concrete with assumed compressive strength of 40MPa was used. Element size of the concrete specimen below the core was 5mm × 5mm × 3.75mm as shown in Fig. 2(c). Element size of other parts of the concrete specimen was 15mm × 15mm × 15mm. A 500mm ×

500mm polyurea sheet was attached under the concrete specimen. The polyurea material was modeled as shown in Fig 3(b). The interface material between the concrete specimen and the polyurea was the nonlinear material shown in Fig 4(b). The "bearing material" in ELS which can transfer only compression was used for the interface between the concrete specimen and the T-shaped steel. A normal steel material was used for the drop weight and the T-shaped steel member.

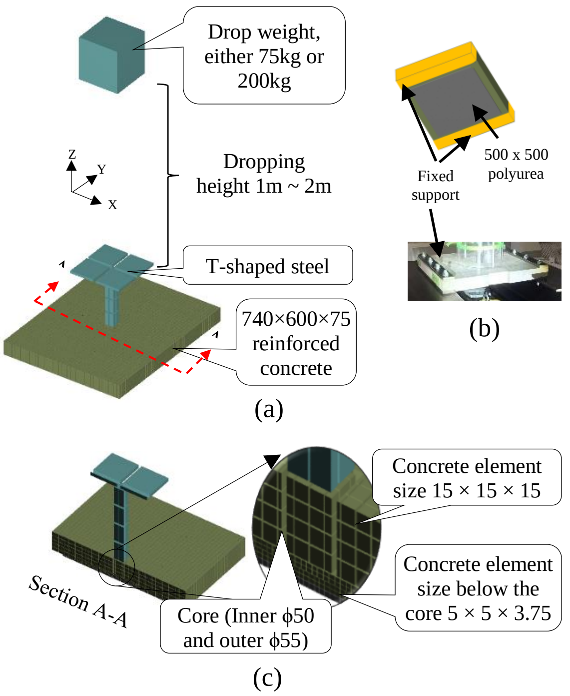


Fig.2 AEM simulation modelling

3.3 AEM Simulation of Case 1 (Using 3mm Thick Polyurea)

In Case 1, a 3mm thick polyurea was attached to the concrete specimen. Element size of the polyurea was 3mm × 5mm × 5mm. The drop weight had a mass of 75kg and fell from 1m height. The kinetic energy of the drop weight at impact was 758J (17% of the strain energy of the PC bar). In the numerical simulation, the dynamic stage had a duration of 0.7s (0.46s to account for the drop weight free fall time + 0.24s for impact and destruction). The time interval was 0.0002s.

For polyurea under tension, the relationship between tensile stress and strain was modeled to be approximately bilinear with strain hardening [12]. In the drop weight AEM simulation, the constitutive model of the polyurea until ultimate strength (22MPa) was implemented through a bilinear material. The Young's Modulus (250MPa) and yield stress (16MPa) of polyurea was calibrated from the drop weight AEM simulation (Fig. 5). To show the stress-strain curve of a polyurea, a simple tension test was carried out using AEM as shown in Fig 3. In the simple tension test (Fig 3(a)), a bilinear material simulating polyuria was used between the concrete and the steel plate. The concrete was fixedly supported. Tension force was applied on the steel plate. The stress-strain curve of the simulate polyurea is shown in Fig 3(b). In the initial region, the stress increases proportionally to the strain. After that the material starts to yield. Then the stress still increases linearly but much more slowly until ultimate strength (22MPa) at a strain of 2.55. Finally, a perfect plastic deformation was followed from a strain of 2.55 to a strain of 3.00.

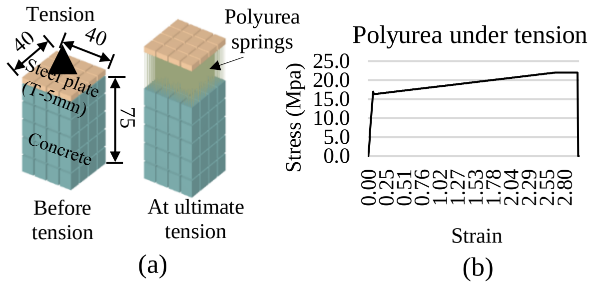


Fig.3 AEM simulation of polyurea under tension

In the drop weight AEM simulation, a nonlinear material showing softening behavior after reaching the maximum stress was used to simulate adhesive between the polyurea and the concrete specimen. The adhesive used in the pull-off adhesion test and in the drop weight experiment was similar. However, the pull-off strength (1.32MPa) from the pull-off adhesion test was small as a concrete cohesive failure was observed due to poor-quality surface concrete despite adhesive failure was expected. Using adhesive strength from the pull-off adhesion test in the drop weight AEM simulation resulted in a total delamination of polyurea despite the experiment as shown in Fig 5. However, a similar drop weight AEM simulation with a 3.4MPa adhesive strength withstand 758J impact energy without total delamination and showed good agreement with the experimental result (Fig 5). In this study, the adhesive strength of 3.4MPa was found appropriate. A simple tension test was conducted using AEM to show the stress-strain curve of this material as shown in Fig 4. In this test, a linear material which shows softening behavior after tensile strength was used between the concrete and the polyurea. The Young's Modulus (4,500MPa) of the primer was calibrated from the drop weight AEM simulation (Fig. 5). The concrete was fixedly supported. Tension force was applied on the polyurea element. The stress-strain curve is shown in Fig 4(b). The maximum tensile stress was 3.4MPa and after that stress softening took place.

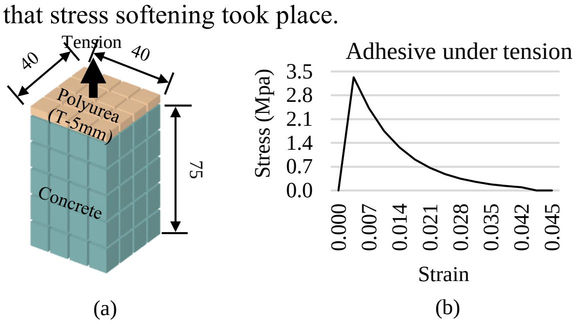


Fig.4 AEM simulation of adhesive material

The polyurea punching test result shown in Fig. 5. Figure 5(a) shows the progressive failure of polyurea and concrete spalling both in the experiment and in the numerical simulation at different time. The concrete under the core crushed instantly after the impact. After that, the polyurea started elongation. In the numerical simulation, a vertical deformation of polyurea was measured. The maximum vertical deformation before cracking appeared in the polyurea was 60mm at 0.48s as shown in Fig. 5(c). In the experiment, a high-speed camera measured the maximum polyurea deformation of 70mm. While the polyurea was elongated, the primer between the polyurea and the concrete was delaminated in 280mm × 280mm area. Delamination area of the primer in the experiment was 275mm × 250mm. After the partial delamination, the polyurea couldn't stretch any longer and was torn, and crushed concrete was observed as shown in Fig. 5(b) and Fig. 5(d).

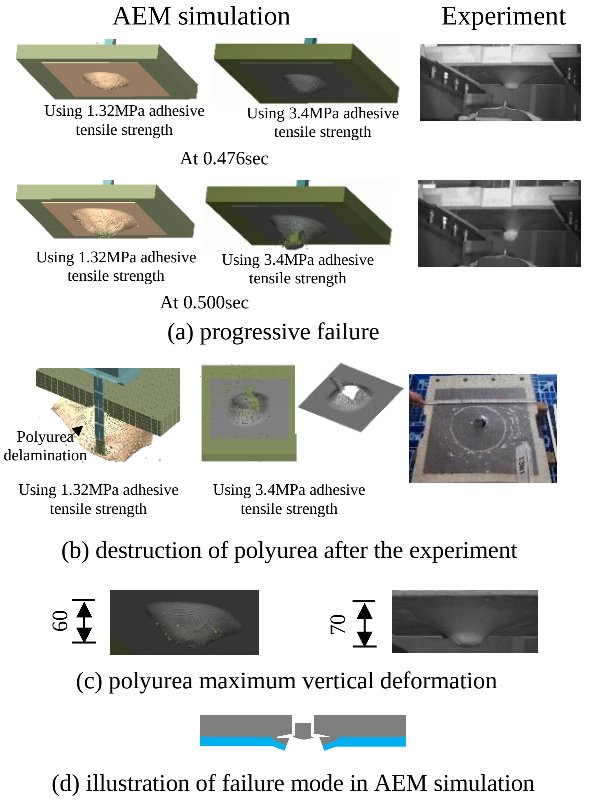


Fig.5 Polyurea punching test (3mm thick polyurea)

In the numerical simulation, the kinetic energy of the drop weight was measured to assess the energy absorption of polyurea as shown in Fig. 6. From 0.00s to 0.458s, the drop weight was freely falling. From 0.458s to 0.460s, the concrete below the core was crushed, and the kinetic energy of the drop weight suddenly dropped from 758J to 342J. After that, the polyurea elongated from 0.46s to 0.50s and the kinetic energy of the drop weight gradually decreased from 342J to 130J. At 0.48s, 1st crack was observed in the polyurea. At 0.50s, the polyurea was torn apart and no longer resisted against the impact loading. The drop weight and the T-shaped steel member freely fell until they impacted the ground surface.

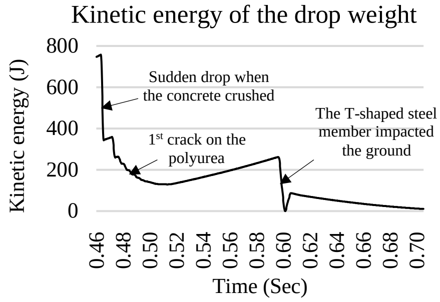


Fig.6 Kinetic energy of the drop weight (Case 1)

In this investigation, a 500mm × 500m polyurea with 3mm thickness couldn't prevent the protrusion simulating 17% strain energy of the PC bar protrusion of 4.5m length.

3.4 AEM Simulation of Case 2 (Using 5mm Thick Polyurea)

In Case 2, a 5mm thick polyurea was attached to the concrete specimen. The simulation model in this case is the same as in Case 1 except that the element size of the polyurea was 5mm × 5mm × 5mm.

Figure 7(a) shows the progressive deformation of polyurea both in the experiment and in the numerical simulation at different time. The concrete under the core crushed instantly after the impact. After that, the polyurea started elongation. Figure 7(b) shows the deformed polyurea after the experiment. In the numerical simulation, a vertical deformation of polyurea was measured. The maximum vertical deformation was 87mm at 0.52s as shown in Fig. 7(c). In the experiment, the maximum vertical deformation measured by the high-speed camera was 85mm. While the polyurea was elongated, the primer between the polyurea and the concrete was delaminated in 410mm × 410mm area. The delamination area of the primer in the experiment was 355mm × 380mm. After 0.52s, the drop weight lost all of its kinetic energy and the polyurea recovered from the maximum deformation. Concrete spalling and cracking in the polyurea were not observed. The illustration of failure mode in AEM simulation is shown in Fig. 7(d).

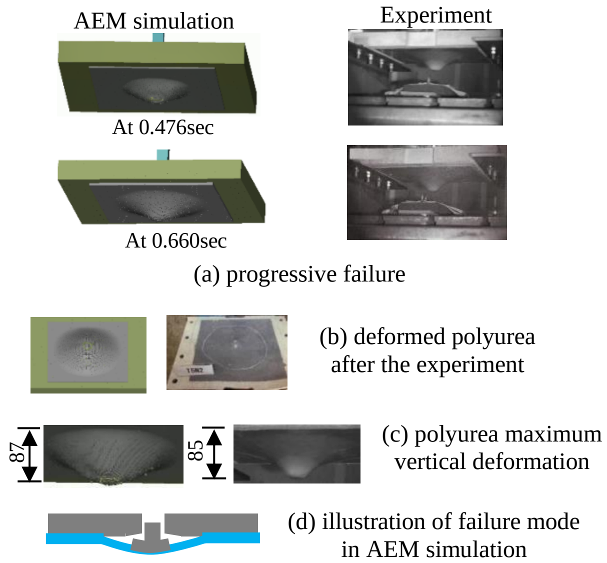


Fig.7 Polyurea punching test (5mm thick polyurea)

In the numerical simulation, the maximum speed of the drop weight at impact was 4.49m/s and the kinetic energy was 758J. From 0.458s to 0.460s, the speed of the drop weight was suddenly dropping from 4.49m/s to 3.00m/s as the concrete was crushing. At the same time interval, the kinetic energy of the drop weight suddenly dropped from 758J to 340J as shown in Fig. 8. From 0.46s to 0.52s, the polyurea elongated gradually until the kinetic energy of the drop weight decreased from 340J to 0J.

In this investigation, a 500mm × 500mm polyurea sheet with 5mm thickness could prevent the protrusion simulating 17% strain energy of the PC bar protrusion of 4.5m length.

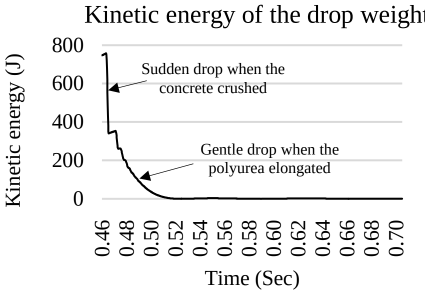
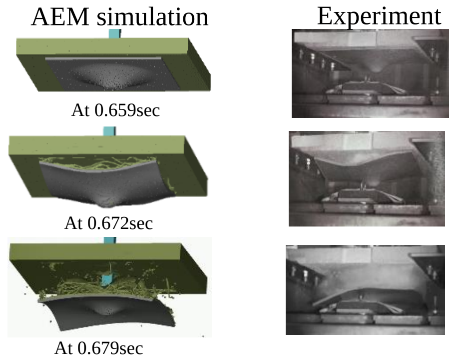


Fig.8 Kinetic energy of the drop weight (Case 2)

3.5 AEM Simulation of Case 3 (Using 10mm Thick Polyurea)

In Case 3, a 10mm thick polyurea was attached to the concrete specimen. Element size of the polyurea was 5mm × 5mm × 5mm. The drop weight had a mass of 200kg and fell from 2m height. The kinetic energy of the drop weight at impact was 3,983J (90% of the strain energy of the PC bar). In the numerical simulation, the dynamic stage had a duration of 1.0s. Two dynamic stages were used. The first one was to account for free falling, while the second one was to simulate the drop weight impact to the concrete and the polyurea. The 1st dynamic stage had a duration of 0.64s with a time interval of 0.01. The 2nd dynamic stage had a duration of 0.36sec with a time interval of 0.00015.

Figure 9(a) shows the progressive failure of polyurea and concrete spalling both in the experiment and in the numerical simulation at different time. Similar to Case 1 and Case 2, the concrete under the core crushed instantly after the impact. After that, the polyurea started elongation. In the numerical simulation, the vertical deformation of polyurea was measured. The maximum vertical deformation before the polyurea was fully delaminated was 100mm at 0.67s as shown in Fig. 9(b). In the experiment, the maximum polyurea deformation measured by the high-speed camera was 116mm. At 0.67s, the polyurea sheet was totally delaminated resulting in falling down caused by the cohesive failure of skin layer of the concrete specimen as shown in the illustration Fig. 9(c). No crack was observed in the polyurea.



(a) progressive failure

(b) polyurea maximum vertical deformation

(c) illustration of failure mode in AEM simulation

Fig.9 Polyurea punching test (10mm thick polyurea)

In the numerical simulation, the maximum speed of the drop weight at impact was 6.31m/s and the kinetic energy was 3,983J. From 0.64s to 0.65s, the speed of the drop weight was suddenly dropping from 6.31m/s to 5.62m/s as the concrete was crushing. At the same time interval, the kinetic energy of the drop weight suddenly dropped from 3,983J to 3,160J as shown in Fig. 10. From 0.65s to 0.67s, the polyurea elongated gradually until the kinetic energy of the drop weight further decreased from 3,160J to 1,376J. After 0.67s the kinetic energy of the drop weight gradually increasing due to gravity as the polyurea and the concrete no longer resisted against the impact load.

In this investigation, 500mm × 500m polyurea sheet with 10mm thickness couldn't prevent the protrusion simulating 90% strain energy of the PC bar protrusion of 4.5m length.

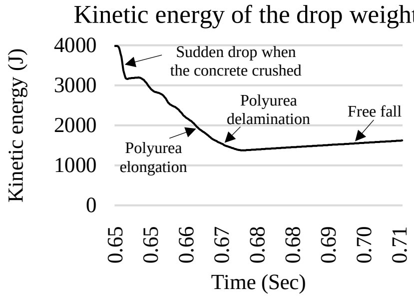


Fig.10 Kinetic energy of the drop weight (Case 3)

In our future investigation, the surface quality of the concrete specimen in the experiment will be improved to avoid concrete cohesive failure during impact. The numerical simulation tool developed in this study will be utilized for evaluating the effectiveness of polyurea against rupture and protrusion of PC bar tendon and concrete spalling in PC bridges.

4. CONCLUSIONS

In this study, the effects of polyurea coating on impact resistance and concrete spalling were numerically investigated. Punching tests of polyurea with a thickness of 3mm, 5mm and 10mm under different impact loads were numerically investigated. The numerical simulations were verified with the experiments. Based on the results obtained in the present work, the following main summary remarks and conclusions can be drawn:

(1) Both numerical simulations and high-speed photography measurements indicated that the polyurea sheet significantly reduced impulsive loads.
(2) Effectiveness of the polyurea sheet depends on impact energy, polyurea thickness, bond strength, primer and quality of surface concrete, etc.
(3) The constitutive model using a bi-linear material for polyurea in the drop weight AEM simulation showed good agreement with the experimental results in terms of impact resistance and failure mode.
(4) A polyurea (500mm × 500mm) sheet with 5mm thickness was effective in resisting against 758J impact energy. However, 3mm and 10mm thick polyurea sheets with 500mm × 500mm were not effective in resisting against 758J and 3,983J impact energy respectively.

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