Multi-bodies impacting a deformable structure

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Abstract

It is of keen interest to understand the interaction of multiple bodies impacting a deformable structure. It is of further importance to understand the errors arising from using simplified versus more accurate representations of the multi-bodies in the numerical scheme used to perform these simulations. In the past, researchers avoided the explicit modeling of the impacting bodies and resorted to the use of a crude pressure-time history representing the transfer of impulse (kinetic energy) from the impacting entities to the target. The reasons for these oversimplifications arose from hardware and software limitations. The drawback is that the errors arising from such an approach were extremely high and, in many cases, unacceptable. The advent, however, of parallel platforms and scalable software in conjunction with more sophisticated material models allows the researchers to approach the problem at hand within a reasonable turn-around time. In the current study only explicit modeling of the impacting bodies will be addressed. The focus of this paper is to present (a) the current methodology for modeling multi-body impact, (b) the possible options of simplified vs. non-simplified numerical simulations, and (c) a measure of error introduced by comparing the two approaches.

Keywords: Multi-bodies; Erosion; Error estimate; Impact; dynamics; Kinetic energy; Constitutive laws; Scalable software

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1. Introduction

The multi-body dynamics of a system has always been of keen interest to the US armed forces and the Department of Defense (DoD). The interaction of multiple bodies impacting a target or targets of different structural and material consistency has been a subject of research for several decades. Limitations in the computational resources, however, did not allow for the accurate modeling of the events and the research was mostly testing and evaluation oriented. The current state of the art in computational hardware and software allows the scientists and engineers to approach the overall problem from a more realistic perspective. The numerical predictions are within tolerable margins of error and, thus, they aid the experimental effort which is reduced or kept to the minimum. In this study a reinforced-concrete (RC) panel is considered. The physical dimensions of the structure are 1.25 m × 1.25 m × 0.15 m. The structure has both primary and secondary reinforcement as well as shear reinforcement. The reinforcing ratios (area based) are, approximately, 1% for the primary and 0.25% for the secondary reinforcements, respectively. The 28-day compressive strength of the concrete does not exceed 35 MPa. The multiple bodies impacting the RC panel are identical in size and shape; rectangular in nature with dimensions of 0.01 m × 0.01 m × 0.04 m. The experimental setup ensures that these bodies attain a stable in-flight velocity of approximately 760 m/s prior to impacting the target. Incident and exit velocities of the impacting bodies are gathered during the experiment and are used in the numerical comparisons that follow.

2. Approach

Finite element analysis (FEA) methods with direct integration schemes are employed to simulate the impact events in this study. ParaDyn [1], a parallel version of DYNA3D, a three-dimensional explicit finite-element program for analyzing the dynamic response of solids and structures, is used for these simulations. ParaDyn has been used as a production tool for many years, as shown by Papados [2,3]. It poses definite advantages as 1) it is a scalable software, running on several parallel

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computer systems and under different message passing protocols, 2) its element formulations include one-dimensional truss and beam elements, two-dimensional quadrilateral and triangular shell elements, two-dimensional delamination and cohesive interface elements, and three-dimensional continuum elements, 3) its library of material behavior includes elasticity, plasticity, composites, thermal effects, and rate dependence, 4) it has a sophisticated contact interface capability, including frictional sliding and single-surface contact, to handle arbitrary mechanical interactions between independent bodies or between two or more portions of one body, and 5) all element types support rigid materials for modeling rigid body dynamics [1]. These features make ParaDyn extremely attractive and efficient to use while the last two features stated (items 4 and 5) are in line with the study presented in this paper. The code resides on several of the five DoD High-Performance Computing and Modernization Program resource centers. The one used in this study is managed by the US Army Corps of Engineers, Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi. All the geometry aspects are taken into consideration in modeling the structure and the impacting bodies. In the RC structure, continuum elements are used to simulate the concrete matrix. The refinement of this structure is such that the aspect ratio for each portion of the analysis does not exceed the three-to-one ratio for any two given sides of the constituent FEA continuum elements. The relative size of the impacting entities compared to those of the RC panel dictate the use of millions of elements in order to keep the aspect ratio rule stated earlier intact. In modeling the RC panel, the reinforcement is modeled using one-dimensional beam elements. Both the one- and three-dimensional elements are allowed to erode subject to a set of plasticity-based threshold criteria which account for differential tensile and compressive behaviors in concrete in conjunction with accumulation of damage or in accumulation of effective plastic strain measures in the case of the reinforcing steel. Figure 1 shows a section of the RC panel with four impacting bodies and part of its reinforcement artificially exposed for visual purposes. Two sets of numerical simulations are carried out: the first one uses impacting bodies which are modeled using non-linear constitutive relations; the second considers impacting entities with an equivalent rigid material formulation. The nature of the RC structure remains the same from the constitutive model point of view. Strain rate enhancements are used in the constitutive models. These enhancements are different in tension and compression for the case of the concrete matrix. The simplest way to compare results from the two approaches is to account for the difference in velocity output (kinetic energy measure) from the multiple bodies at the end of the numerical simulation. Since the RC structure is massive compared to the impacting bodies and since it does not deform or displace during the event, the assumption is that most of the difference in kinetic energy is attributed to the plastic work done in permanently deforming the impacting entities. In the case where the rigid body approach is employed, no plastic work is present in the impacting bodies and, thus, the comparison of these two approaches is deemed valid provided that 1) the friction laws used in the modeling of the two events is identical and 2) the induced relative crater formation (if any) is approximately the same for the two events. Eqs. (1) through (3) can be used to provide a measure of the energy expended in performing plastic work (degree of plastification).

$$\Delta \mathbf{E}^{\mathbf{e}} = \mathbf{KE_o} - \mathbf{KE_f} \qquad \forall\, \mathbf{e} \in \Omega_{\mathbf{ibs}} \tag{1}$$

$$\sum(\mathbf{e}) \equiv \Omega_{\mathbf{ibs}} \tag{2}$$

$$\sum(\Delta \mathbf{E}^{\mathbf{e}}) = \Pi_{\mathbf{i}} \tag{3}$$

Eq. (1) represents the difference in the kinetic energies of the impacting elements on each body before ($\mathbf{KE_o}$) and after ($\mathbf{KE_f}$) impact. Eq. (2) represents the overall domain defined by the impacting elements, $\Omega_{\mathbf{ibs}}$, and Eq. (3) is the summation of these energies into a scalar quantity, $\Pi_{\mathbf{i}}$, which is a measure of the plastic work (based on the assumptions stated earlier).

A more accurate but also more cumbersome measure of the plastic work accumulated during the event is to account for the actual plastic work for each of the individual elements comprising the global impacting entities, $\Omega_{\mathbf{ibs}}$, and, subsequently, estimating the overall work according to Eq. (4).

$$\Pi_{\mathbf{i}} = \sum \left(\sigma_{\mathbf{ij}} \varepsilon_{\mathbf{ij}}^{\mathbf{plastic}}\right)_{\mathbf{e}} \quad \forall\, \mathbf{e} \in \Omega_{\mathbf{ibs}} \tag{4}$$

3. Discussion and summary

Figure 2 shows the damage on a portion of the slab and the relative damage at the end of the simulation. It is apparent that not only the impacting elements are considerably distorted (a large amount of plastic work is exhibited) but, moreover, the numerical unbalance that is introduced affects the exit path and orientation of these bodies. Although not shown, in the case of the rigid body impact the exit path is in line with the entry path, unless the penetrating body is impacting a reinforcing element (large stiffness element) in which case the exit path is affected by the contact–impact dynamics of the two bodies. The energy dissipated in the plastic work accounts for approximately 17% of the initial kinetic energy using Eqs. (1–3) and 16% using Eq. (4). This is a substantial amount of energy dissipation. It appears to be consistent with a variety of targets and

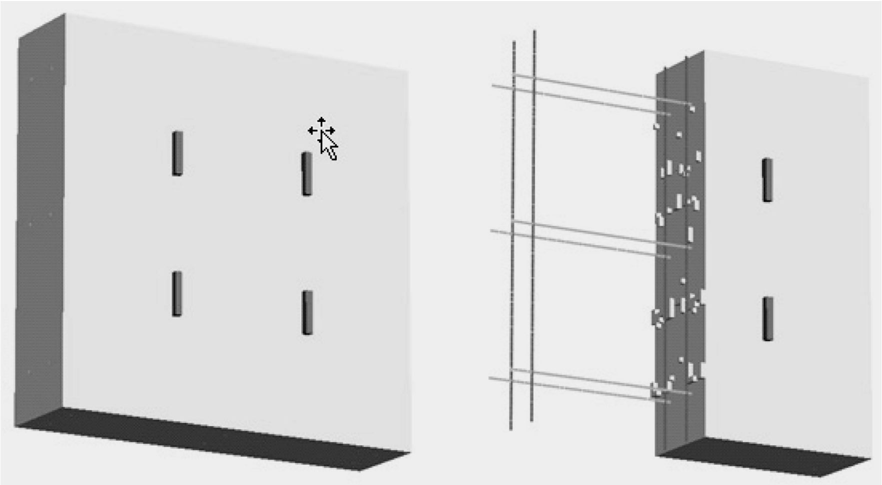


Fig. 1. Section details of the RC panel.

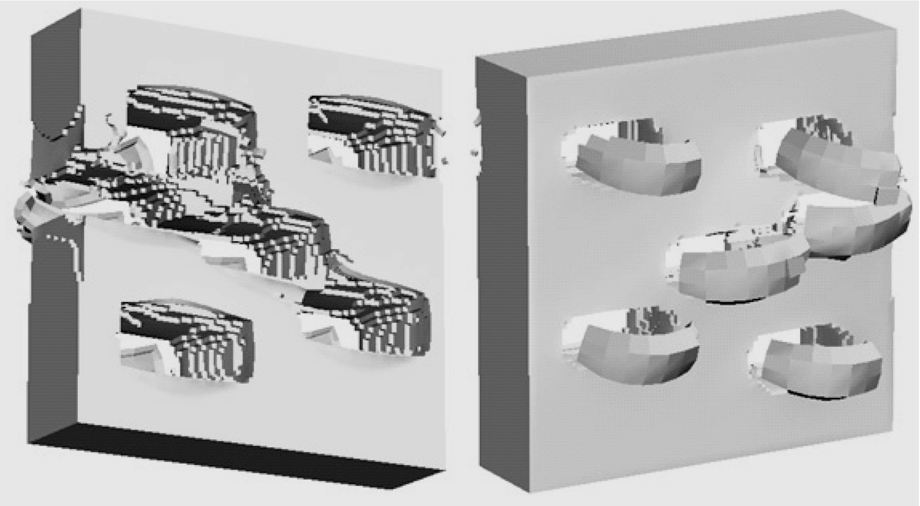
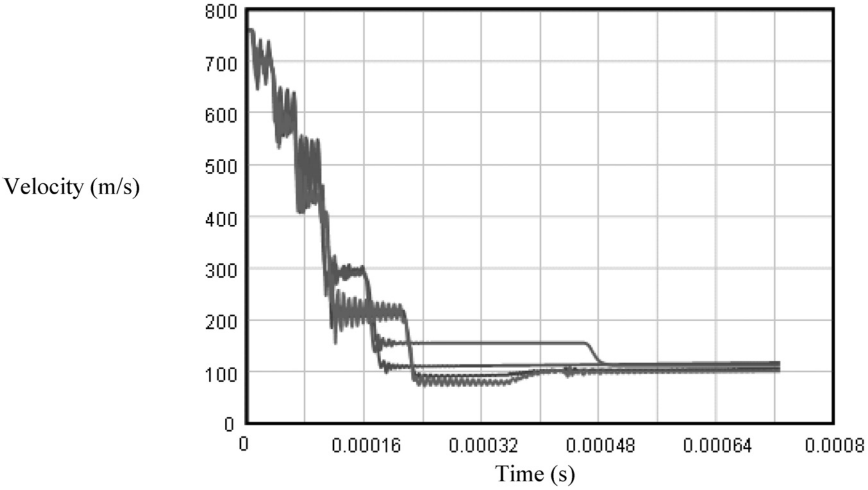
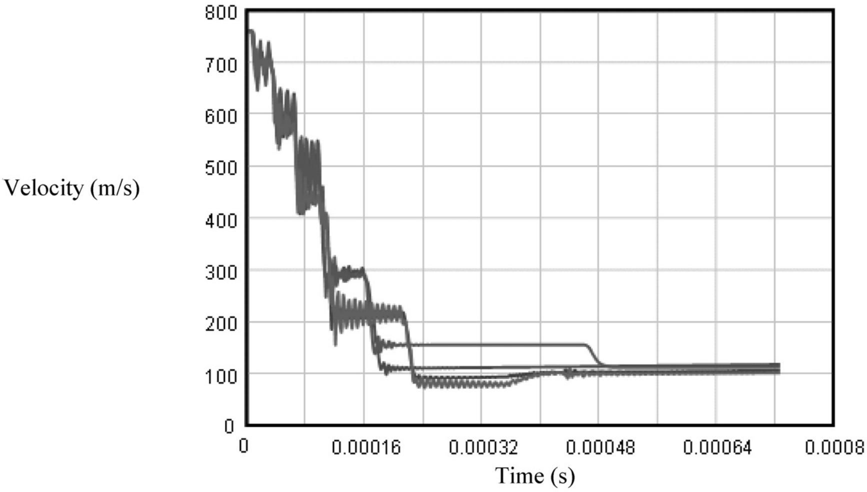


Fig. 2. Front (impact side) and back (exit side) of damaged panel section.

penetrating elements provided that 1) breaching occurs and 2) the relative stiffness of the impacting bodies to that of the target is larger by at least an order of magnitude. Figure 3 shows the time-varying velocity-distributions of select impacting elements for the two cases considered, the flexible and rigid impacting bodies. Although problem dependent, an approximate 12% difference is observed between the average exit velocities for this specific problem. The question that remains to be answered is whether the same approach is valid in the event that the multi-body impact does not allow for total perforation of the target, such as the event shown in Fig. 4. In this case, damage is incurred to the panel section, cratering and ejecta are formed, and there is still substantial deformation on the impacting bodies. This is a much harder problem to quantify than the one stated earlier. A number of options must be consideration for these simulations (e.g. allowing for strike and stick conditions, strike and bounce conditions, or a combination of the two, considering the total momentum/KE of the ejecta, etc.) that can result in significant difference in the overall estimation. In this particular example, approximately 9% of the energy was dissipated in the plastic work using either Eqs. (1–3) or Eq. (4). Although not as high as the 17% observed in the previous example, it is still considered to be significant and should be taken into consideration.



(a) Flexible Impacting Body Method



(b) Rigid Impacting Body Method

Fig. 3. (a) Deformable vs. (b) rigid velocity output for select impacting bodies.

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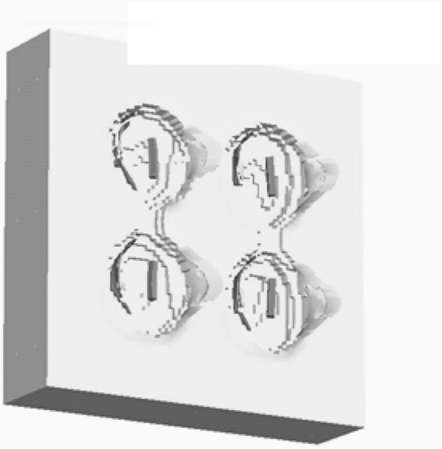
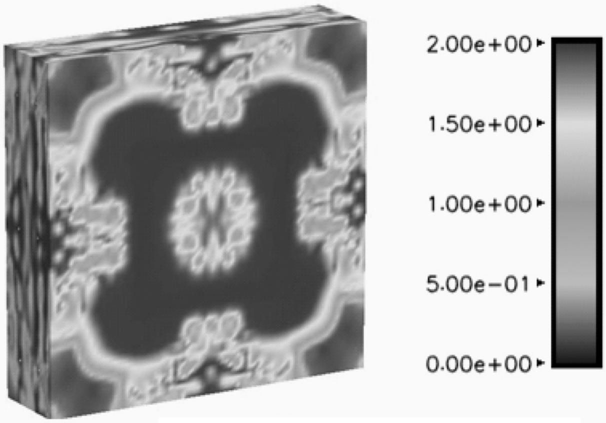
(a) Front (Impact) Face



(b) Back (Away from Impact) Face



Material damage varies from 0 to 2, where:
0 – No damage,
1 – Onset of yield, and
2 – No tensile capacity (only compressive), i.e. geologic behavior

Fig. 4. (a) Material damage and (b) damage measure of non-penetrating impact bodies.

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