A PREDICTIVE COMPUTER PROGRAM FOR PROACTIVE DEMOLITION PLANNING

Quarterly Progress Report
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1. Background and Introduction

Bridges represent a significant subpopulation of our civil infrastructure. Majority of them are deteriorating fast and in need of replacement or rehabilitation. The first step of those replacement/rehabilitation projects is typically to either entirely or partly demolish the existing structure. Therefore, proactive planning for controlled demolition is of utmost importance to proceed with the rest of construction project in a timely manner. Maintaining the integrity of neighboring infrastructure (e.g., permanent roadways, nearby transmission lines) and the safety of workers are critical issues, for which contingency plans also must be developed based on any feasible emergency scenarios.

However, little effort has been given to develop better removal techniques of existing structures, while great effort has been made to design/construction techniques for new structures. Planning failure is often unpredictably realized in the demolition project due to inherent uncertainty hard to characterize ahead, not only in the deteriorated condition of the structure that may be far different from that of the original design, but also in the mode of destruction that may depend on adopted demolition methods, types and performance of destruction tools (e.g., wrecking ball, cutter, crusher, hammer, etc.), dismantling sequence and associated change in the remaining structural capacity during the demolition process.

It is typically hard to develop a general guideline/specification that can facilitate safe and efficient demolition, and very limited information has been available to guide structural engineers and contractors on how to proceed with the demolition of an existing structure. This lack of generalized procedure has led to structural engineers and contractors approaching the demolition work differently, and as a result, most states neither specify parameters for demolition equipment nor require the submission of contractor qualifications with the demolition plans [1].

2. Problem Statement

The potential hazards and inefficiency may be better controlled and possibly eliminated by leveraging computer simulation that can help realistically predict the demolition process. However, such computer tools for simulation-aided demolition planning remains to be developed in the bridge engineering community. This study aims to enhance the predictive capabilities by developing a numerical simulation technique that can realistically model, simulate and visualize the bridge demolition, which will better support the engineers and contractors' decision making.

3. Research Approach and Methods

Simulation of bridge demolition is a challenging problem that requires to numerically model initiation and propagation of cracks in the material due to mechanical impact by demolition equipment, and break-up of the structure into pieces. The interaction between the bridge and the demolition equipment, and the corresponding deformation of damaged bridge and displacement of debris are physically complex phenomena, for which material transition from a continuous medium to multiple broken (discontinuous) pieces needs to be realistically modeled. To this end, this project adopts a discrete mechanical simulation technique for high-fidelity simulation of such destruction problems, which commonly model a continuum as a discrete system that is composed of bonded rigid or deformable elements.

4. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 – Literature Review

The objective of this task is to make comprehensive literature review regarding the relevant research efforts that have been made to simulate bridge demolition process using discrete mechanical simulation technique. Related literature has been extensively reviewed, and brief summary of the findings is provided as below:

Based on the literature review, it was concluded that there are largely two different types of approaches can be made depending on the order of dynamics adopted for the simulation: (i) force-based or (ii) impulse-based dynamic approach.

(a) Force-based dynamic approach has been widely adopted for discrete mechanical simulations. The interaction of modeled elements is explicitly considered through a set of springs and dashpot, thus often called mass-spring-dashpot system. The bond is modeled to be broken if the tensile force exceeds a threshold, and elements separated, which is the major difference from continuum mechanics frameworks such as the finite element method (FEM). The discrete element method (DEM) is currently the most popular force-based numerical method in the field of computational discrete mechanics, and has been widely adopted in a number of cross-disciplinary applications to model the discontinuities in material and structural systems, e.g., collapse of unreinforced masonry structures [2], material fracture [3][4], progressive collapse of building structures [5], etc. The force-based (or acceleration-based) dynamics approach is based on the ordinary 2nd order dynamics (i.e., $f = ma$), thus computationally demanding in general especially with the required simulation fidelity. The time step size Δt is also limited by the stability criterion for explicit numerical time integration which is, in turn, determined by modeled element size. In this way, a very small Δt is typically used in DEM simulation coupled with needed double-precision for the numerical stability can result in significant computational costs. This major computational bottleneck has significantly limited DEM application to relatively small-scale engineering problems.

(ii) Impulse-based dynamic approach is the other class of discrete mechanical simulation technique often adopted to realistically present larger scale discrete bodies' interactions. The impulse-based dynamics employs a reduced 1st order dynamics to directly manipulate the velocity of discrete elements (i.e., $i = m\Delta v$) compared to the 2nd order dynamics that works on the integration of accelerations as used in the conventional DEM. The time step size Δt is limited by the physics of the problem whereby a too large time step size will result in elements passing through each other, but not limited by numerical stability and very small Δt unlike DEM. Hence, significant numerical efficiency is demonstrated with almost two orders of speed-up, while the physical plausibility is still maintained. Consequently, it takes only a few days to simulate a large scale multi-body problem, which typically takes several months if the computationally intensive DEM is used to simulate the same problem. However, the contact force is not an integral part of simulation, which is the major drawback of the impulse-based dynamics approach, as the primary variables are collision impulse and velocity, not contact force and acceleration that are still required for engineering applications. Recently, impulse-based DEM (iDEM) was developed based on the impulse-based dynamics that retrieves the 2nd order engineering details lost (i.e., contact force) due to the order reduction in the equation of motion, which enabled the impulse-based dynamics suitably adopted for engineering simulations [6]. As an incentive, the impulse-based dynamics approach will allow for more simulations to be performed for a given time while physical plausibility being maintained. Therefore, this approach will enable to better characterize and identify the most likely critical scenarios in a demolition project ahead.

Task 2 – Design of the Overall Architecture of the Simulation Framework

The objective of this task is to design overall architecture of the program, which includes various numerical components required to simulate the demolition. In particular, balancing between simulation fidelity and computational efficiency will be pursued as the computational framework to be developed in this study targets solving a field scale problem for use in the engineering practice, which is different from a conventional fracture mechanics solver that focuses on the precise crack propagation at a relative small scale.

Figure 1 overviews the overall calculation flow of the simulation framework, which is mainly composed of 2 parts, i.e., the impulse-based dynamic simulation (Part 1) and the retrieval of the 2nd order engineering details (Part 2). The 1st part corresponds to Stages 1 to 6, while the 2nd part corresponds to Stage 7 in the figure. This framework adopts the conventional algorithm/code used in open source physics engines, e.g., Bullet [7], for the impulse-based dynamic simulation (Part 1), and adopts/modifies the algorithm in [6] to develops the retrieval part as an add-on (Part 2).

In Stage 1, the initial conditions such as element shapes, orientations, sizes and other modeling properties are defined such as the coefficient of restitution. Voronoi tessellation [8] is adopted for the domain discretization and the pre-fragmentation of bridge members to be destructed. The initial list of neighboring elements will be then developed. In Stage 2, the initial velocity is updated by integrating the body force over the given Δt. This initial velocity calculation will be mostly used for the trajectory motion update of the demolition debris after onset of breaking and the demolition tools such as wrecking ball. In Stage 3, the code performs the neighbor search to find nearest elements. The list of close pairs will be updated as the simulation of demolition proceeds. A general neighbor search algorithm such as Two Level Search [9] will be used. In Stage 4, more accurate geometric test is performed to find the contact points between colliding element pairs. In Stage 5, the collision impulse is computed, for which the solver iteratively goes through all the contact points between the colliding element pairs until the specified collision law is numerically satisfied.

The velocity from collision is then updated. In Stage 6, the element position is finally updated. In Stage 7, i.e., Part 2, the 2nd order engineering details are retrieved from the computed collision impulse.

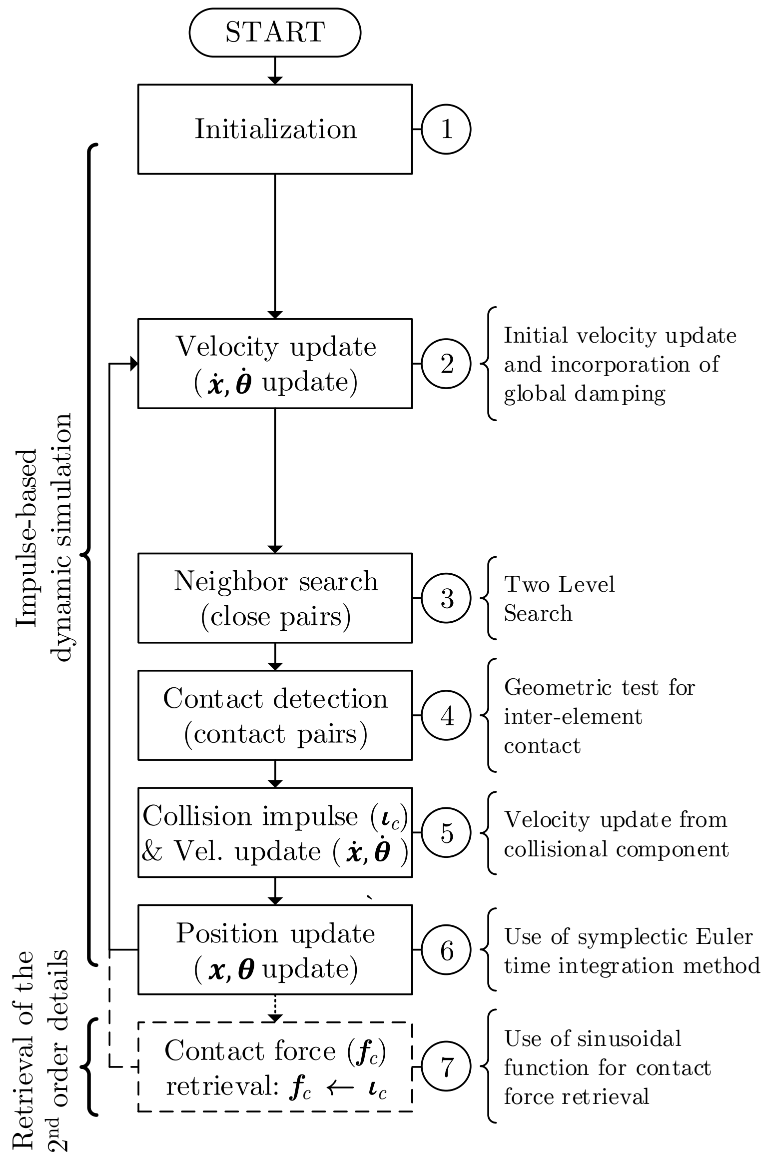

Figure 1. Calculation flow of the simulation framework with the stage number shown in circle

Task 3- Code Development

The objective of this task is to implement numerical components, and particular focus will be given to the retrieval of the 2nd order engineering details lost (i.e., contact force) due to the order reduction in the equation of motion. The implementation will be done in an object-oriented manner for the code extensibility to facilitate implementation of any further ideas even after this project is completed. This project does not consider hardware acceleration technique such as general-purpose computing on graphics processing units due to the limited project timeframe. However, the implementation will be made with possibility open to the parallel computation capability that may be added later. Therefore, single instruction multiple data implementation will be considered. The development is currently in progress.

The team is working on the code implementation for simulation of explosion as one of the major methods of bridge demolition. Explosion is defined as sudden release of energy that creates outward propagating pressure front which is known as blast wave. The blast wave is approximated as an expanding spherical wave with a pressure profile. This pressure is a function of time that can be defined as the following equation known as Friedlander equation:

$$p(t) = p_0 + P_s^+ (1 - \frac{t}{T^+}) e^{bt/T^+} \tag{1}$$

where p_0 is the ambient pressure, P_s^+ is the peak overpressure, t is time measured from the arrival time, T^+ is the time duration of the positive phase when pressure is more than the ambient pressure and b is a constant [10]. The pressure will be applied as a force to the surrounding bodies as the following equation:

$$\vec{F} = p(t)A \frac{\vec{R}}{\|\vec{R}\|} \tag{2}$$

where $p(t)$ is the pressure generated by explosion, A is the projected area of a body and $\vec{R}$ is the position vector which takes the distance of the body from source of explosion into account. As far as our approach to the problem is impulse-based (not force-based), the force is converted to impulse at each time step. If the impulse applied is greater than a threshold defined, the constraints between meshes will be broken. The code development is currently on the process.

Task 4- Verification, Calibration and Validation

The objective of this task is to verify the numerical issues in the developed program. Any major programming issues/errors will be also resolved/debugged through the verification process. The program will be also calibrated and validated using physical testing data and available video records obtained from the previous demolition projects. To assess computational efficiency and simulation fidelity, large scale multi-body simulation will be performed and benchmarked against any published simulation data.

The simulation visualization is not only important for facilitating the validation of the simulations in comparison to the actual bridge demolitions in the field, but also required for engineers and stakeholders to have a clearer view of various demolition scenarios in the decision making process. This visualization processing in this project is performed by leveraging Blender [11], which is a free and open-source 3D computer graphics software toolset. Blender is widely used for creating animated films, interactive 3D applications and even video games. Moreover, Blender adopts Bullet [7] as one of the main physics engines and shares some common modeling procedures, e.g., Voronoi tessellation for discretization. Therefore, use of Blender facilitates to visualize the implemented idea in Bullet. Preliminary effort has made for the visualization of bridge demolition for different demolition scenarios. For each of these, the effort has been given to reproduce the videos of actual bridge demolition cases. In order to reach to a level of plausibility, the values of key parameters related to simulation process in software are calibrated by trial and error procedure until a reasonable level of plausibility is obtained in the simulation mimicking the real demolition.

A set of simulations have been already carried out in order to reproduce the I-235 Bridge demolition project. The bridge is modeled with the actual dimensions (including span length, deck width, pier height), structural element sizes, mass and mechanical properties and then discretized in Blender to estimate a set of different demolition scenarios through simulations. The demolition of I-235 Bridge demolition was done by utilizing a wrecking ball, for which three set of simulations are carried out for one span, two span, and three span bridge respectively. Figure 2 and 3 show the footage of the one span bridge demolition after the other decks were already destructed. Figure 4 and 5 show the demolition simulation visualized by Blender. There are a set of physics modeling parameters need to be calibrated for realistic simulations. Table 1 shows the key parameters used for the reasonable plausibility of the demolition. Figure 6 and 7 show the I-235 Bridge with two spans remaining after all the other decks were destructed. Figure 8 and 9 show the corresponding visualization performed using the exactly same set of physics modeling parameters calibrated with the demolition simulation of I-235 Bridge with the single span (Figure 4 and 5). The impact of the location on the three span bridge is then simulated to estimate the influence of different impact points of the wrecking ball. Four different simulations are performed for four different impact locations as shown in Figures 10 to 13.

Figure 2. I-235 Bridge with a span about to be demolished by dropping a wrecking ball

Figure 3. The one last remaining deck of I-235 Bridge demolished by the wrecking ball

Figure 4. The one span I-235 Bridge modeled

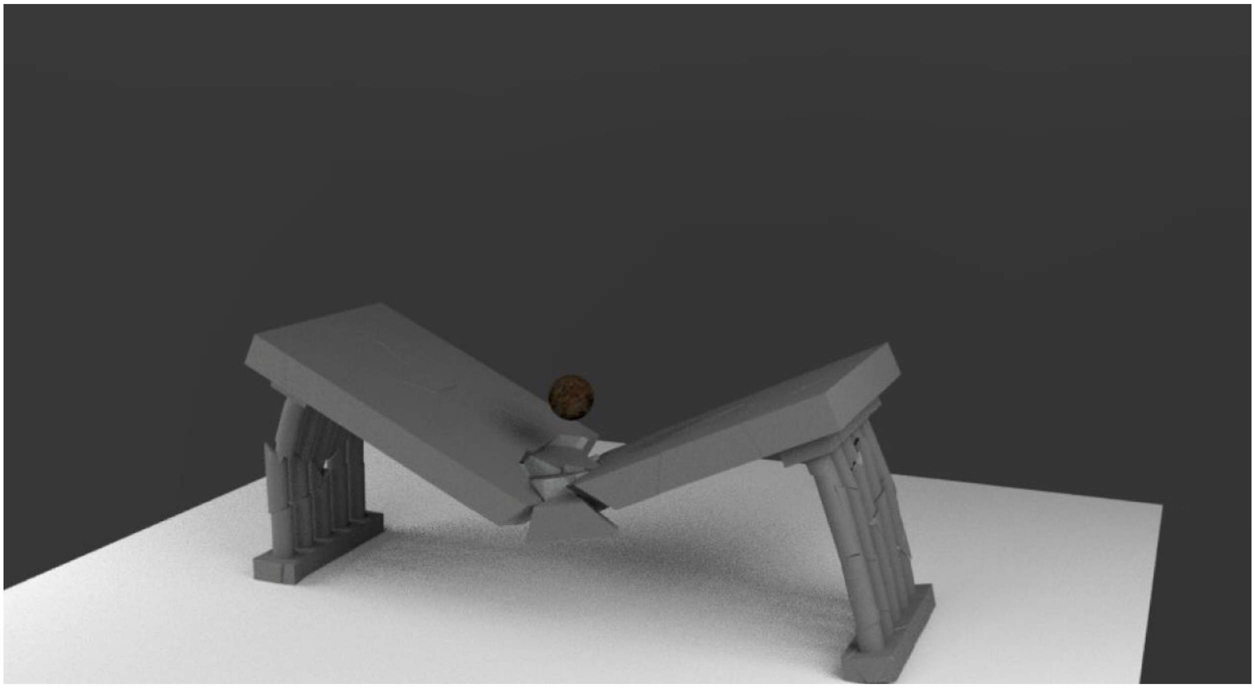

Figure 5. Simulated demolition of the one last remaining deck of I-235 Bridge

Table 1. List of key parameters for the demolition simulation of I-235 Bridge

Parameter	Values
Bridge Mass (single span)	107,000 kg
Wrecking Ball Mass	10,000 kg
Fracturing Algorithm	Voronoi Boolean
Shard Count	200
Constraint Method	Vertex
Constraint Type	Hinge
Constraint Limit per mesh island	50
Search Radius	1.00 m
Constraint Breaking Threshold	10000 kgf

Figure 6. I-235 Bridge with two spans about to be demolished by dropping a wrecking ball

Figure 7. The one of the remaining decks of I-235 Bridge demolished by the wrecking ball

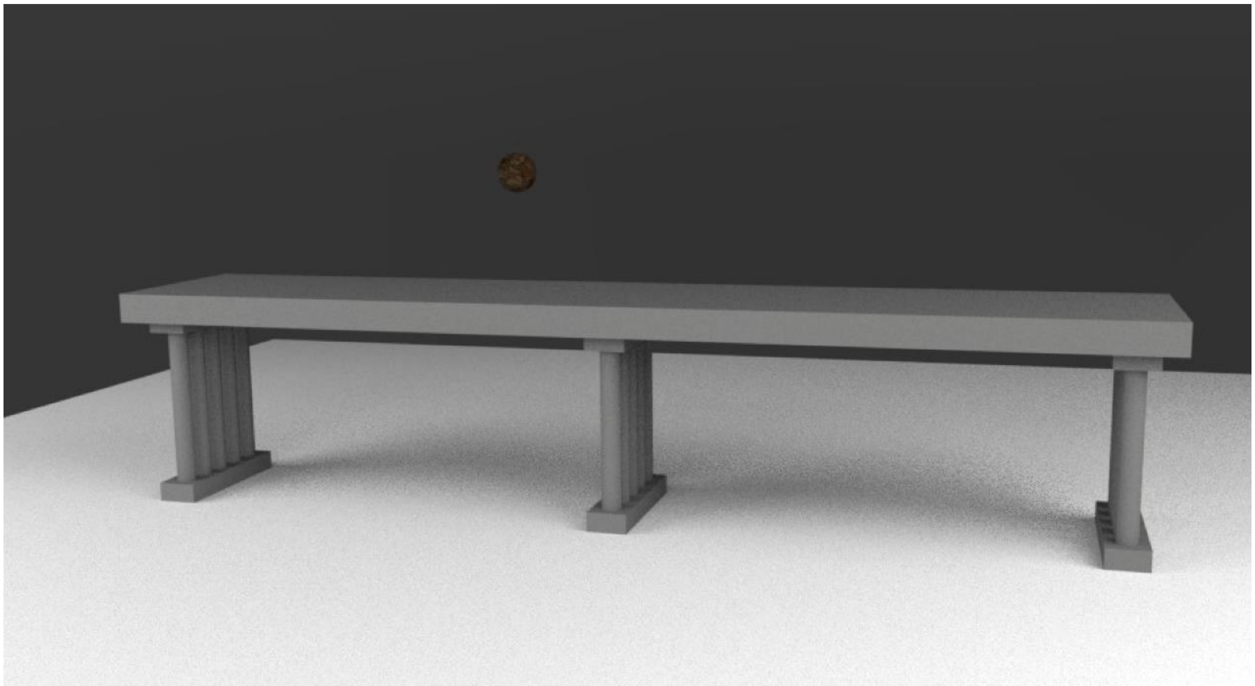

Figure 8. The two span I-235 Bridge modeled

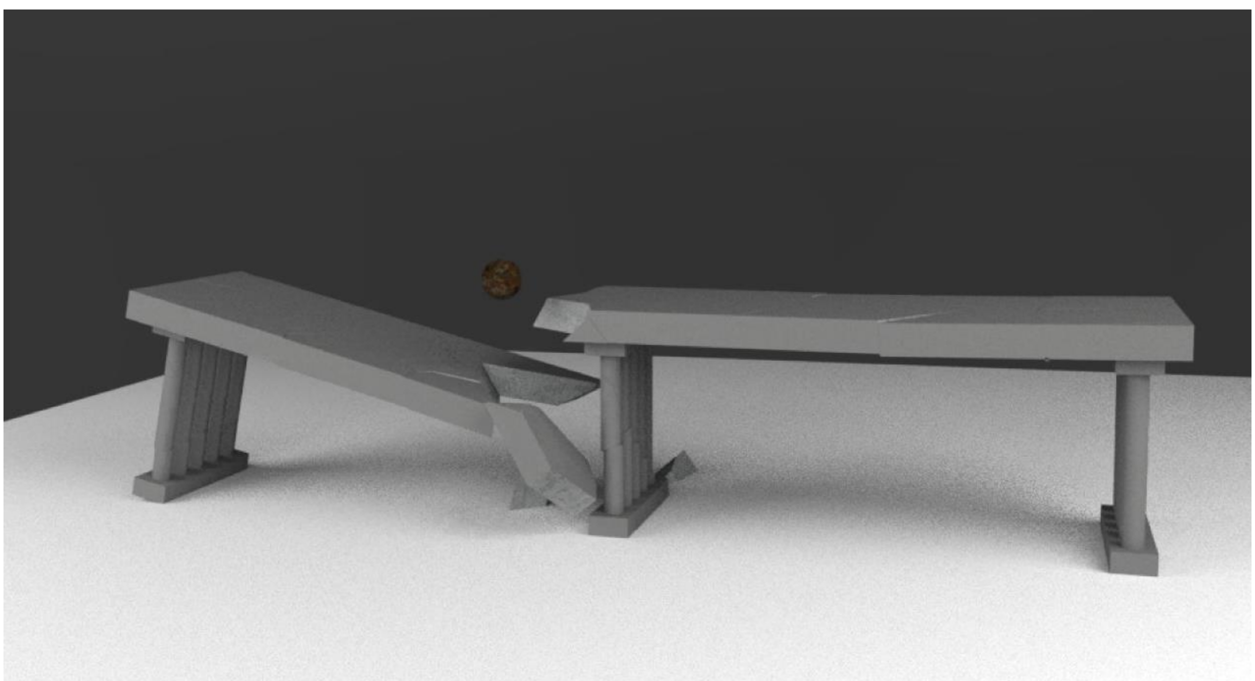

Figure 9. Simulated demolition of the one of remaining decks in I-235 Bridge

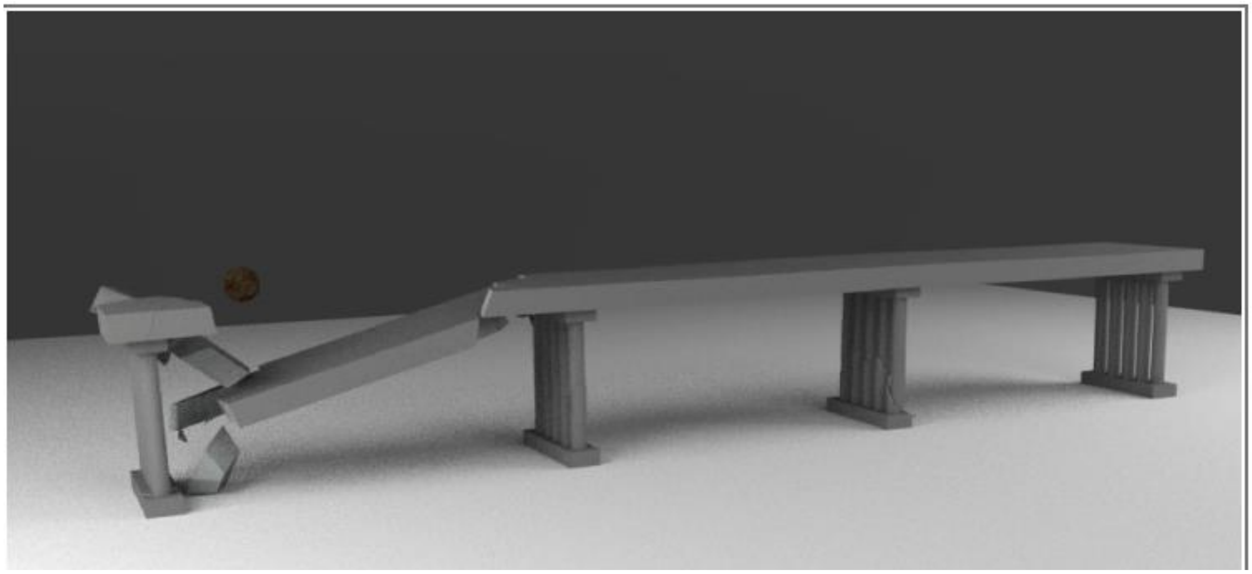

Figure 10. Simulated demolition of the three span I-235 Bridge, where the wrecking ball is dropped near the end of the bridge

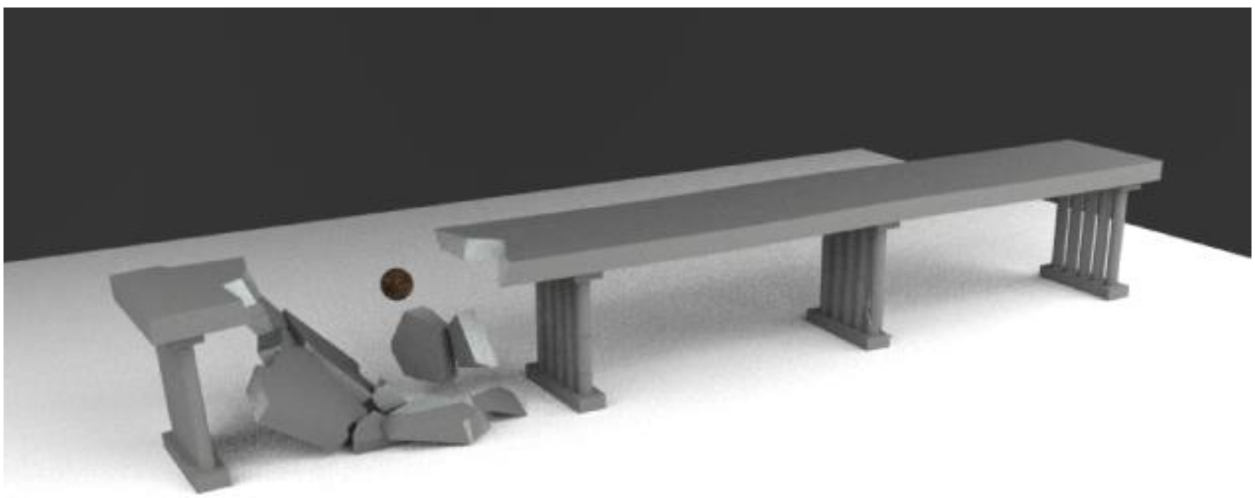

Figure 11. Simulated demolition of the three span I-235 Bridge, where the wrecking ball is dropped near the center deck of the bridge.

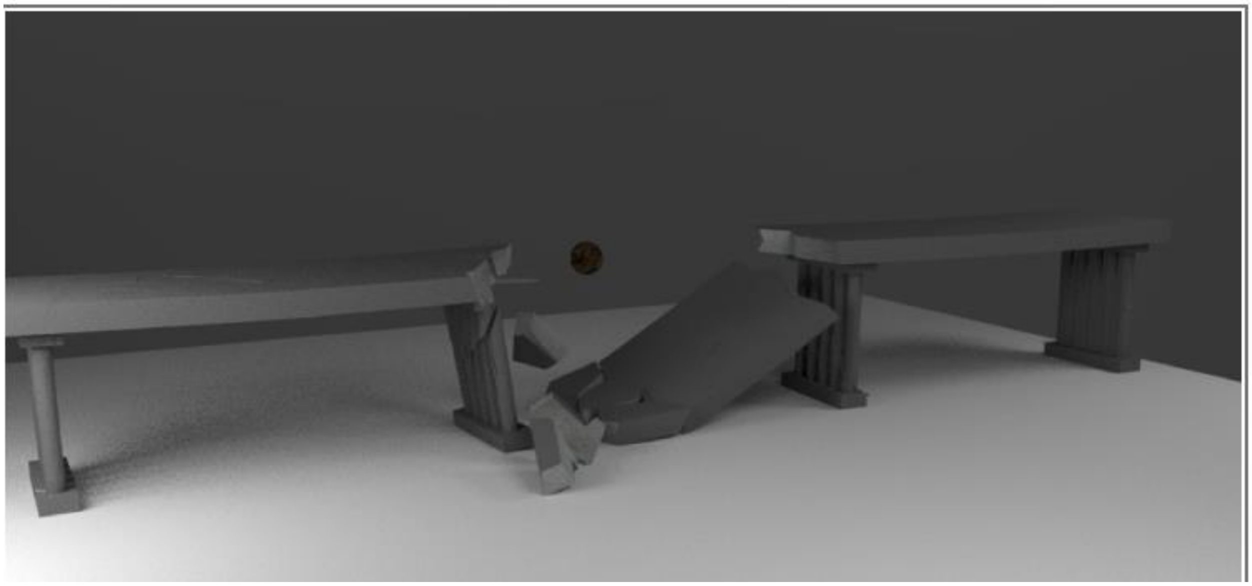

Figure 12. Simulated demolition of the three span I-235 Bridge, where the wrecking ball is dropped on the center deck of the bridge; the hitting point is in the middle of the bridge center and the neighboring deck on the left

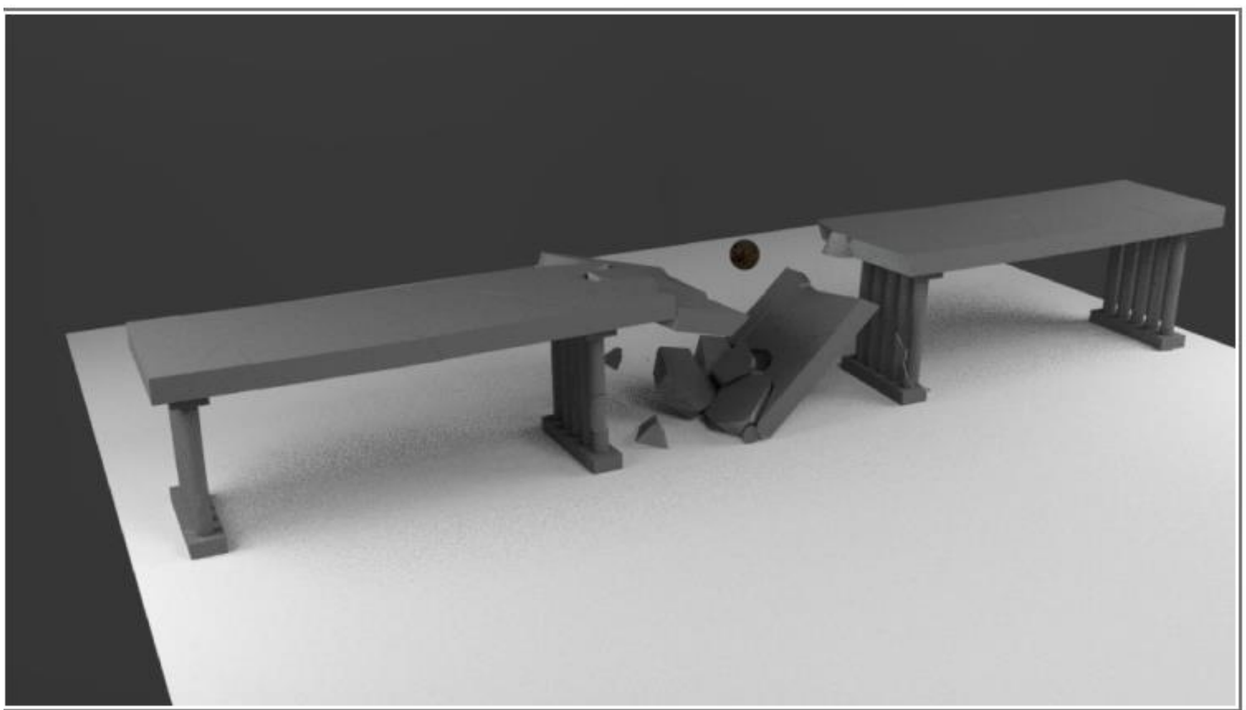

Figure 13. Simulated demolition of the three span I-235 Bridge, where the wrecking ball is dropped on the bridge center

Figure 14 shows the dismantling demolition using a jackhammer. The corresponding simulation is shown in Figure 15 that presents a good realism. Reproduction of this type of demolition requires relatively fine mesh compared to the wrecking ball demolition simulation above, which is therefore computationally more expensive.

Figure 14. Dismantling demolition using a jackhammer

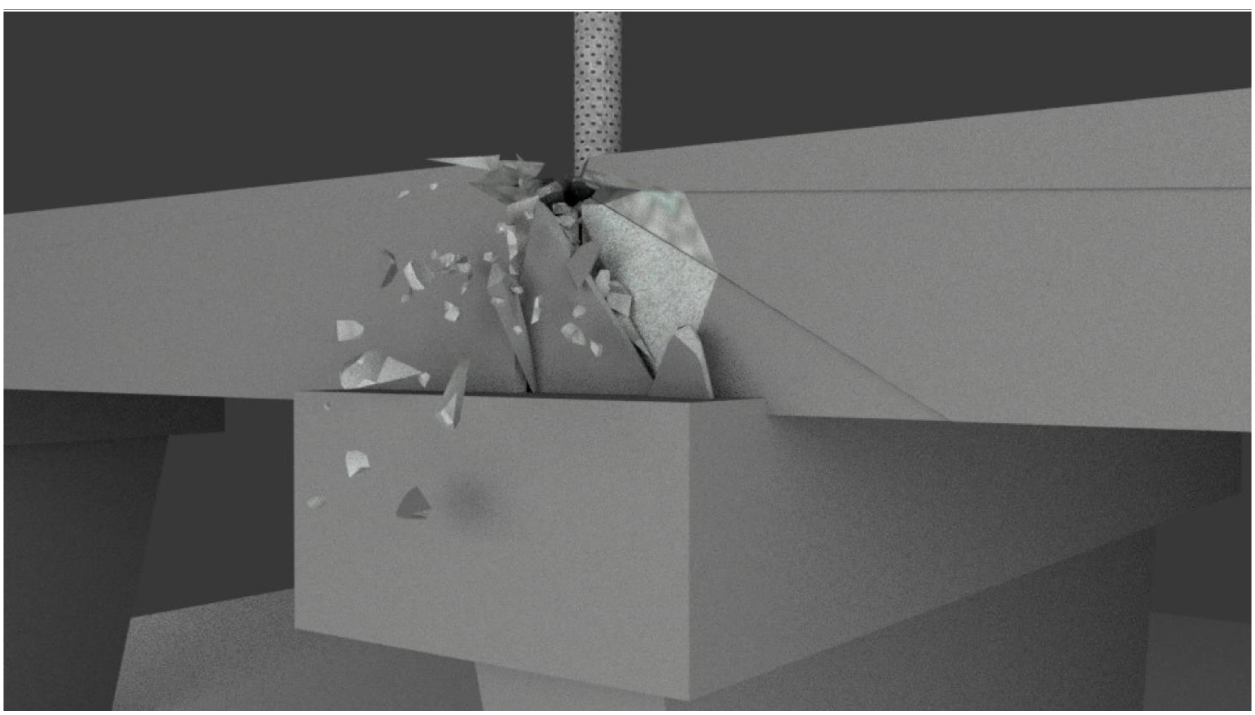

Figure 15. Simulated demolition by jackhammer

Task 5- Final Report

Final report will be developed to provide the instructions as step-by-step procedures. Tutorials will be included to showcase simulation of example demolition projects. No work on this task has been done to date.

5. Expected Results and Specific Deliverables

The project deliverables will be in the form of computer program that enables modeling, simulation and visualization of bridge demolition. The proposed development plans to adopt existing freeware (that is freely re-distributable under a public license) for pre- and post-processing, such that anyone can use the software package without any licensing issues. The final report with tutorials will be also provided as a deliverable in the package.

6. Schedule

Progress of tasks in this project is shown in the table below.

	Month																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Task 1																			
Task 2																			
Task 3																			
Task 4																			
Task 5																			

Work performed

Work to be performed

7. References

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