Breakable Elastic-plastic Constraint for Rigid Body Simulation

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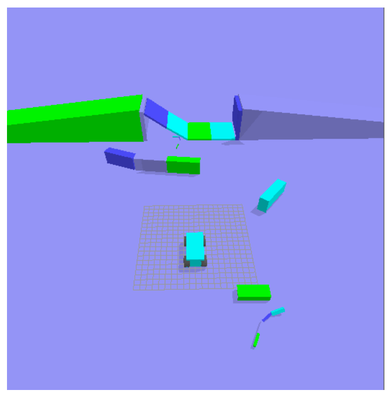

Figure 1. Adding ductile breakable constraint to popular open source physics engines Bullet Physics and Box2D allows more realistic simulation of many scenarios.

Abstract

This paper introduces simple and efficient method to simulate ductile fracture in existing impulse-based physics engines. Method is based on technique of splitting bodies to multiple pieces and joining them with constraints. Constraints are described using body dimensions and material parameters.

Sample programs with source code are made available to allow developers already using Bullet Physics and Box2D to add plasticity into their simulations.

1. Introduction

Theory for handling of plasticity in computer graphics has been presented already 1988, [Terzopoulos and Fleischer 1988]. Recent paper by Jones provides extensive listing of related work during past decades, [Jones et al. 2016].

In impulse-based phycis engines most breakable scenarios are implemented by destructing various bodies based on collision or impulse exceeding predefined limit. Nevertheless, breaking of steel or reinforced concrete structures using this approach

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is not appropriate if the simulation is to look realistic.

More realistic simulation of ductile destructable bodies is possible but in many cases it would require selecting of new physics engine.

Our approach This study will introduce an approach to account for plastic deformation in impulse-based phycis engines. Presented methodology does not require significant software development efforts from game vendors and is thus easily adoptable. In the introduced method, plastic deformation takes place if the force or moment exceeds a predefined limit, deformation absorbs energy and joint breaks if plastic capacity is exceeded. Maximum forces and moments are estimated based on the plastic section modulus. Joint breaking is based on summing plastic deformation and comparing it to a predefined material based limit. The elastic part of deformation is modelled by employing modification of an existing constraints.

Limitations Forces are calculated by dividing impulse by timestep and maximum impulse is calculated by multiplying maximum force by timestep. This means that simulation of quick interactions requires small timestep. This limitation is not introduced by this approach but is build in feature of impulse-based simulation.

Multiaxial stress is not taken into account.

2. Description of plasticity in the framework of physics engines

In this work simulation of breaking of bodies made of ductile material is made more realistic by splitting the rigid body to multiple bodies that are connected by energy absorbing joints.

Stress-strain behaviour of ductile steel A typical engineering stress-strain curve of ductile steel is shown in Figure 2.

In Figure 2, σ is stress, E is Youngs modulus and f_y is yield stress. Engineering stress and strain mean that original dimensions are used in stress calculation, [Dowling 2007]. The stress-strain curve is not drawn to scale as elastic strain could not be seen as it is typically 0.001 to 0.005 and fracture strain can be 100 times larger. In practice this means that elastic displacement due to axial forces is usually not visible. Visible elastic displacement is usually due to bending.

In this work, an elastic-fully plastic material model is used in most scenarios. Having elastic part allows elastic displacements for slender structures. Elastic material behavior is ignored in approach introduced in this work if the deformation is related to a higher frequency than integration stability would allow. It should be noted that geometry of bodies is not updated during analysis and thus engineering stress-strain properties are used.

In this work, strain hardening is taken into account by assuming that plastic vo-

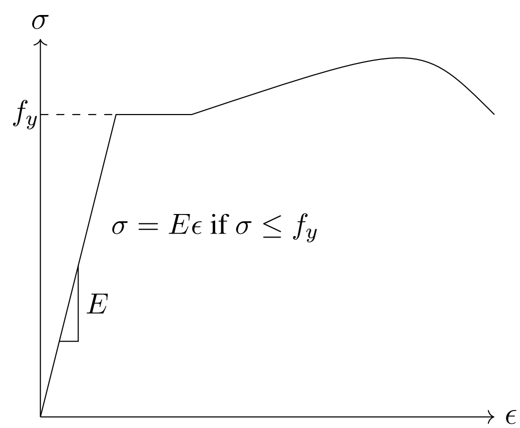

Figure 2. Engineering stress-strain curve of ductile steel (not to scale).

lume in bending expands, [Dowling 2007]. Material that starts to yield first is hardened and as a result of which yielding moves. The difference between the elastic and plastic section modulus is depicted in Figure 3.

As shown in Figure 3, if stress is below yield limit f_y, stress and strain are linear within the material. If cross section is fully plastic, stress is assumed to be at yield level over the whole cross section such that the plastic section modulus is higher than the elastic section modulus.

Plastic capacities In this work, plasticity is handled by defining maximum forces using plastic capacities, which are defined below.

Maximum force acting in a direction of $\vec{r}^{\,i}_{anc}$ is product of area and yield stress as follows:

$$N_{max} = \int_A f_y. \tag{1}$$

Maximum forces acting perpendicular to $\vec{r}^{\,i}_{anc}$ are a product of area and shear yield stress τ_y as follows:

$$Q_{max} = \int_A \tau_y. \tag{2}$$

Maximum moments acting around the axis perpendicular to $\vec{r}^{\,i}_{anc}$ are integrals of the perpdendicular distance and yield stress f_y as given for the moment around the x-axis and moment around the z-axis, respectively:

$$M^x_{max} = \int_A z f_y, \tag{3}$$

$$M^z_{max} = \int_A x f_y. \tag{4}$$

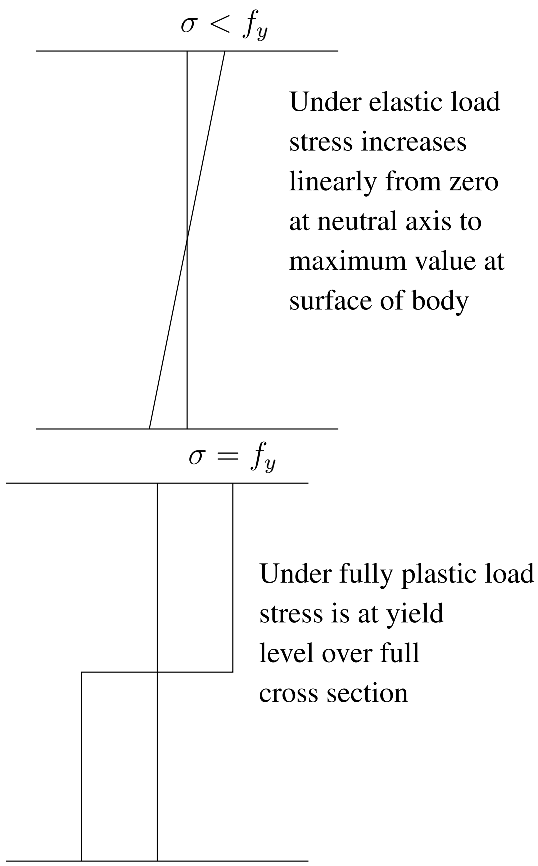

Figure 3. Axial stress distribution over a cross section for bending under elastic and fully plastic loads.

Maximum moment around $\vec{r}^{\,i}_{anc}$ is an integral of distance d from the joint point and shear yield stress τ_y as:

$$M^y_{max} = \int_A d\tau_y. \tag{5}$$

Maximum forces and moments for a rectangular section with width b and height h using constant yield stress are given in Table 1. Yield shear stress is assumed to be $0.5\ f_y$ using the Tresca yield critetion. If the von Mises yield criterion is used 0.5 is replaced by 0.58 $(1/\sqrt{3})$, [Dowling 2007]. These are not exact values in a multiaxial stress state but they should be acceptable in most gaming scenarios.

For torque there is a closed form solution only for circular cross sections. Given approximation is best suited for cases where b and h are similar. Better approximation for any given b and h can be obtained by integrating distance from the center of the joint over cross section and multiplying it with the yield shear stress e.g. using Octave, [Eaton 2016]. An example of calculation of the maximum moment around $\vec{r}^{\,i}_{anc}$ is

Direction	**Maximum value**
maximum shear force	$0.5\, b\, h f_y$
maximum normal force	$b\, h\, f_y$
maximum bending moment in direction of h	$0.25\, b\, h^2\, f_y$
maximum bending moment in direction of b	$0.25\, b^2\, h\, f_y$
maximum torque	$\approx 0.19\, b\, h\, \frac{b+h}{2} f_y$

Table 1. Maximum forces and moments for rectangular section with width b and height h using constant yield stress f_y

```
b=0.01; h=0.01; fy=200e6;
wpy=fy/2*dblquad(@(x,z)...
 sqrt(x.*x+z.*z),-b/2,b/2,-h/2,h/2)
38.2
```

Listing 1. Calculation of maximum moment around $\vec{r}^{\,i}_{anc}$ using Octave.

shown in Figure **??**.

Joint breaking

3. Implementation for Box2D

4. Implementation for Bullet Physics

References

DOWLING, N. E., 2007. Mechanical behavior of materials - engineering methods for deformation, fracture, and fatigue, third edition. 2, 3, 4

EATON, J. W., 2016. Gnu octave. URL: https://www.gnu.org/software/octave/. 4

JONES, B., THUEREY, N., SHINAR, T., AND BARGTEIL, A. W. 2016. Example-based plastic deformation of rigid bodies. *ACM Trans. Graph. 35*, 4 (July), 34:1–34:11. URL: http://www.cs.ucr.edu/~shinar/papers/2016_example_based_deformation.pdf, doi:10.1145/2897824.2925979. 1

TERZOPOULOS, D., AND FLEISCHER, K. 1988. Modeling inelastic deformation: Viscoelasticity, plasticity, fracture. vol. 22, ACM, 269–278. URL: http://web.cs.ucla.edu/~dt/papers/siggraph88/siggraph88.pdf. 1

Index of Supplemental Materials

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