Breakable Elastic-plastic Constraint for Rigid Body Simulation

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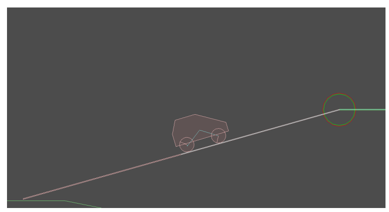

Figure 1. Adding ductile breakable constraint to popular open source physics engine Box2D allows more realistic simulation of many scenarios. In picture above ramp is under elastic loading.

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. Procedure to provide realistic parameters for constraints is described. Procedure may be based on body dimensions and material parameters or desired bahviour.

Sample program with source code are made available to allow developers already using 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. This provides simple means for visualization of explosions and high speed collisions on brittle structures. Nevertheless, breaking of steel or reinforced concrete structures using this approach is not appropriate if the simulation is to look realistic or structures should not fail completely.

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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 can be estimated based on the plastic section modulus or by defining maximum elastic displacement or based on desired capacity. Joint breaking is based on summing plastic deformation and comparing it to a predefined material and geometry based limit. The elastic part of deformation is modelled by employing modification of an existing constraints.

This paper follows idea of allowing game designers to get desired behaviour without diving into details of structural engineering. Idea was presented by Catto, [Catto 2011]. Basic idea is that game designer selects spring frequency so that integration is stable. Downside is that constraints will be quite soft. In our method game designers get new option to use rigid-plastic 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. Bending moment - normal force interactions and multiaxial stress are not taken into account. Simulation of many bodies connected by constraints

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. Ha-

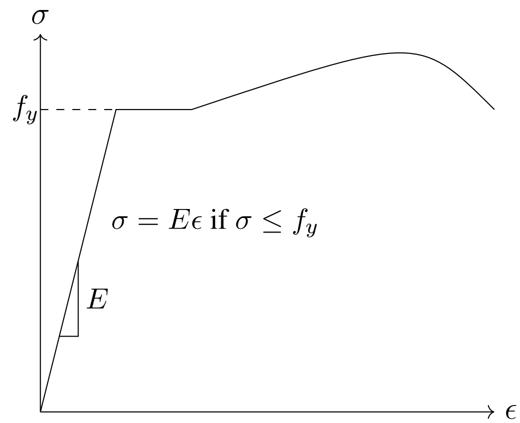

Figure 2. Engineering stress-strain curve of ductile steel (not to scale).

ving 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 volume 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 based on dimensions and material 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 moment is integral of the perpdendicular distance and yield stress f_y as given for the moment around the z-axis:

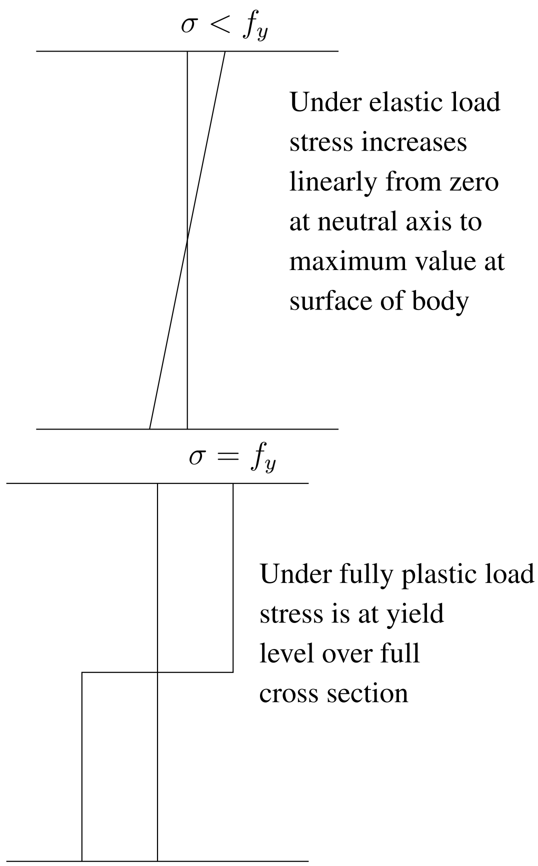

Figure 3. Axial stress distribution over a cross section for bending under elastic and fully plastic loads.

$$M_{max}^{z} = \int_A x f_y. \tag{3}$$

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.

Plastic capacities based on desired behaviour Capacities can also be defined directly based on desired scenarios. E.g. joints for bridge can designed so that maximum shear force is larger than weight of heaviest vehicle so that all vehicles can drive to bridge. Maximum bending moment could be set so that joint will start to rotate when heaviest vehicle is near the middle of bridge.

For elastic-plastic cases maximum capacity can also be defined by setting maximum elastic displacement or rotation.

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	$0.25\,b\,h^2\,f_y$

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

Joint breaking Joint breaking is based on summing of plastic displacement or rotation. Process can be subdivided few phases.

1. Hitting maximum impulse value triggers additional processing.
2. New neutral position is calculated so that elastic part is subtracted from current position.
3. Plastic strain or rotation is incremented.
4. Current plastic strain or rotation is compared to maximum value and joint is broken if current value exceeds predefined maximum value. This part can be finetuned e.g. so that joint is not broken during compression if connected parts are made of material which can handle large strains due to compressive forces.

3. Implementation for Box2D

b2ElasticPlasticJoint implementation is based on b2WeldJoint which implements rigid and flexible joints as described in Catto's paper [2011] on soft constraints. Main idea is that game designer should not have find suitable values to get desired functionality but constraint is configured by giving desired damping ratio and frequency. This principle leads in many cases to quite soft constraints to keep simulation stable. b2WeldJoint supports also rigid joint in which case iterative solver creates some flexibility. If maximum forces and moment are set to very high value b2ElasticPlasticJoint behaves like b2WeldJoint but is slighly slower.

Changes to processing In addition to allowing definition of maximum forces and moment during initialization b2ElasticPlasticJoint allows definition of maximum moment by giving maximum elastic rotation.

For each step maximum rotational impulse and linear impulses are calculated using step length and current orientation of the joint.

During solution phase impulse is clamped so that it does exceed predefined limit. If clamping is activated additional processing is done at the beginnig of next step to update neutral position and increment plasticity values.

Debugging tools Box2D testbed offers many useful tools and only few additions were made for testing of plasticity.

1. Tunable visualization of joint forces
2. Numerical output of joint forces as absolute values and as percentage of maximum forces
3. Numerical output of usage of plastic capacity
4. Selection of joints for display of numerical values

3.1. Examples

Cantilever beam

Multifloor frame

Car Dynamic bodies are car (680 kg), wheels (50 kg for each axel), and ramp (2160 kg).

Ramp is joined to fixed part with b2ElasticPlasticJoint having frequency of 1 Hz. Maximum elastic rotation is set to 0.12 and maximum plastic rotation to 0.4. With this configuration own weight or ramp uses about 13 % of plastic capacity. After first jump about 50 % of plastic capacity is used. Each additional jump uses about 7 % of plastic capacity.

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Index of Supplemental Materials

1. Box2D source with plasticity extensions https://github.com/simo-11/Box2D

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