

Virtual Crash Testing of Palletized Loads through Physics-Based Simulation

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Abstract

Crash tests on loaded pallets are essential to ensure cargo stability during transport, as sudden accelerations or decelerations can cause loads to shift, topple, or become damaged. However, physical testing is costly, time-consuming, and destructive. To address these challenges, we present a virtual approach using physics-based simulation to model pallet behavior under realistic transport scenarios. In our method, both boxes and the stretch wrap are simulated using Extended Position-Based Dynamics (XPBD). Boxes are treated as rigid bodies, while distance constraints applied to the outer layer of the stack reproduce the compressive forces of real wrapping. Wrap failure is modeled by removing overstretched constraints, enabling the simulation of tearing events. Moreover, the widespread use of plastic wrapping has driven research into eco-friendly alternatives. Our simulation provides a safe, cost-effective way to evaluate such materials, supporting the study of pallet crash scenarios and laying the foundation for future improvements in physical realism, contact handling, and validation against real-world test data.

CCS Concepts

• **Computing methodologies** → *Physical simulation; Modeling methodologies; Simulation by animation;*

1. Introduction

In the logistics of food and beverage transportation, palletized loads represent the standard method for road freight. These consist of a wooden pallet onto which multiple layers of boxed products—such as bottles or cans—are systematically arranged. The packaging process is finalized by *wrapping* the entire assembly, thereby securing the load for transit.

Current safety regulations mandate that companies evaluate each product type prior to transport, ensuring compliance with food safety and stability standards. Specifically, these regulations define tolerance thresholds for palletized loads under directional acceleration forces (*crash tests*). Specifically, the European Road Worthiness Directive [eur14] lays the foundation for the EUMOS 40509 [eum20] standard, which defines the procedures for conducting crash tests on palletized units. This standard outlines how to assess real-world transport conditions, such as acceleration, braking, and turning, and provides detailed criteria for evaluating load rigidity and deformation. One way to conduct a physical test is by loading a truck with the units to be evaluated and driving it in a controlled, safe environment. An alternative approach involves using specialized testing equipment, such as the machine developed by ESTL Company [est25]. This device features a movable platform, called a sleigh, on which the pallet is placed, and an engine capable of generating a constant and controlled horizontal acceleration impulse, while the movement is being filmed by high-speed

cameras. The results of these tests determine whether a palletized unit meets the required safety thresholds or fails to comply.

Packaging configurations can vary across layers to accommodate different product types and handling requirements. In addition, wrapping materials are crucial for maintaining load stability; plastic films such as heat-shrink wrap and LLDPE are commonly used [MMJ21] for this purpose. A growing trend is the adoption of paper-based wrapping to reduce plastic usage, though this introduces challenges like increased tear susceptibility. Given the diversity of pallet setups and the need for safety validation, traditional testing methods—such as physical truck trials and the ESTL machine—are often impractical. Truck tests involve safety risks and fuel consumption, while the ESTL system is resource-intensive and limited to single-load evaluations, requiring numerous tests to cover all configurations.

A solution, based on Digital Twins, has been proposed in [SMI*25], where the authors simulate the ESTL machine and its dynamics in a virtual environment, using physical engine of Blender. That simulation aims to allow for full control over pallet configurations and simulated movements, enabling accurate assessments of load stability without the limitations of physical testing. However, significant challenges still hinder the adoption of such a prototype. The wrapping material must not only withstand external forces, such as pressure from the internal boxes and the effects of gravity, but also exert a compressive force on the contents.

The two-way interaction between the internal components (product packs and wooden pallet) and the external envelope (the wrapping) remains an open problem in physical cloth simulations.

In this work, we propose an alternative approach to model these interactions, based on Extended Position-Based Dynamics (XPBD). In this paradigm, the packages are modeled as rigid bodies, while the wrapping is represented through distance constraints applied to the outer layer of the stack, effectively mimicking the compressive forces exerted by real-world wrapping. The simulation provides a controlled environment for systematically analyzing failure cases in virtual pallet crash tests.

2. Method

We adopted the Extended Position-Based Dynamics (XPBD) algorithm [MMC16] as the core of our simulation framework. The main motivation lies in its robustness, numerical stability, and efficient handling of complex constraints, providing unconditional stability while maintaining real-time performance. Its formulation enables the simultaneous simulation of rigid bodies with accurate collision handling and soft constraints that capture the cohesive effect of the wrapping film.

The crash test is modeled as rigid bodies (stacked boxes) interacting through collisions and distance constraints that represent the wrapping film. XPBD handles both within a unified framework, ensuring realistic dynamics and cohesive behavior.

Collisions between boxes are detected using the Separating Axis Theorem (SAT), and the Sutherland–Hodgman algorithm is then applied to determine the precise contact points. Collision response is handled within the XPBD framework by formulating these contacts as positional constraints, ensuring stable interaction between the boxes. XPBD for rigid bodies [MMC*20] provides a systematic approach to friction handling, allowing physically realistic contact behavior during collisions.

The wrapping film is modeled as a network of distance constraints connecting points on the external faces of the boxes within the stack. These constraints are distributed according to a grid that spans the stack (see Fig. 1), generating forces that keep the boxes cohesive, approximating the effect of a physical wrapping film. In the XPBD framework, each distance constraint is defined between two attachment points belonging to different boxes and is characterized by a resting length, which represents the target distance in the absence of deformation. During the simulation, as the boxes move and rotate, the current distance between the points generally deviates from this resting length. The distance constraint function can be expressed as

$$C(\mathbf{p}_i, \mathbf{p}_j) = \|\mathbf{p}_i - \mathbf{p}_j\| - d_0,$$

where \mathbf{p}_i and \mathbf{p}_j are the world positions of the two attachment points and d_0 is the resting length. The XPBD solver then enforces the constraint by iteratively adjusting the positions and orientations of the rigid bodies along the gradient of the constraint function, effectively pulling the points back toward their target distance. In this way, the distance constraints prevent lateral sliding and enforce cohesion, producing an emergent behavior in which the stack reacts as if it were actually wrapped.

We then carried out simulations on real palletization configurations, subjecting the system to an acceleration phase followed by a deceleration until complete stop. Figure 2 shows a representative frame of the simulation, rendered in Blender.

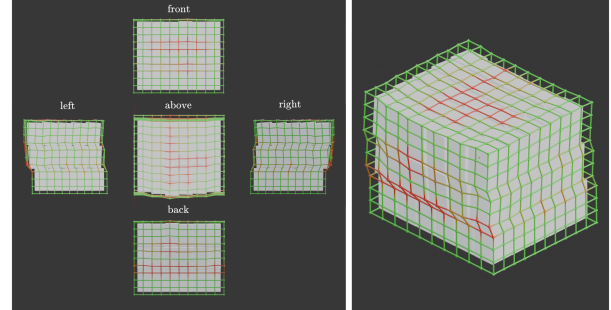


Figure 1: Visualization of the wrapping constraints during the acceleration phase. The five planes of the stack are shown on the left and an isometric view on the right. Constraints are color-coded by stretching, from green (rest length) to red (maximum deformation).



Figure 2: Render of the simulation during the acceleration phase.

3. Conclusions and Future Works

Our method explores a novel approach to virtual simulations in packaging crash tests, limiting the consumption of resources and time. The modeling of the wrapping forces around the pallets as distance constraints allows for a simple but easily adaptable solution for physical simulations in this industrial applications.

The two-way interaction, however, is a problem that is not limited to our setting. In cloth physical simulation the most common engines support the deformations of the garments as consequence of body movements, nevertheless, there is no standard regarding the deformations of the body subjected to the elastic forces of the clothes. A possible followup to our work could be the extension of our approach to the physical simulation of the clothes with the two-way interaction, modifying also the concept of skinning of the more common used avatar frameworks, expanding the impact of our approach to multiple fields.

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