Two-handed Tangible Interaction for Physically-based 3D Deformation

Nawel Takouachet* Nadine Couture*+ Nicolas Verdon* Pierre Joyot* Patrick Reuter*+◊▼ Guillaume Rivière*
*ESTIA +LaBRI ◊INRIA ▼Univ Bordeaux Segalen

ABSTRACT

Physically-based methods ensure an accurate simulation of the realistic behavior of virtual 3D objects. In this paper, we define a novel approach to use tangible user interaction combined with a mechanical solver for simulating physically-based deformations. The user directly controls the resulting geometry of the virtual 3D object by means of intuitive two-handed manipulations of a deformable input device.

We describe the simulation steps and address the difficulties related to the communication between the three main components: the input device, the virtual 3D object, and the physical solver. We present a prototype framework for running bending and twisting beam deformations. In particular, we explore the potential of the ShapeTape, a sensitive malleable strip, as input peripheral for controlling the user interactions.

Our work is an excellent educational tool for understanding mechanical phenomena. It is also applicable in an archaeological context in order to understand the chronology of the different deformations that were suffered by archeological findings.

KEYWORDS: Tangible Interface, Two-handed Interaction, Physically-based Deformation, ShapeTape.

INDEX TERMS: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Input devices and strategies.

1 INTRODUCTION

Virtual 3D modeling and deformation offer a high potential to improve applications in various domains, such as animation, design, styling, biomedicine and education. In all these domains, the majority of systems operate through mouse, keyboard, or touch-screen interaction. The users still have a high cognitive load concerned with the computer interface, thus being distracted from the actual task.

Recently, many research efforts investigate new input devices that enable the development of much more intuitive interaction systems, such as virtual environments (VR) or tangible user interfaces (TUIs). The aim is to make the user interaction with the virtual object easier and more natural, by using senses to structure the environment like the real world, as for example hands to touch and manipulate, or voice to speak and operate.

The contribution of this work is to bring up a new and challenging approach by offering a tangible user interface for direct physically-based deformation of virtual 3D objects that can be visualized in real time. More precisely, we define a novel interaction system that makes it feasible to link natural bi-manual gestures such as bending, twisting, compression and traction with mechanical actions that interactively affect the geometry of the virtual object according to the physical laws.

Our contribution is based on the three following pillars:

- ***Fully tangible interaction:*** The virtual object is physically incarnated in the input device. The user feels like if he really takes the object entirely in his hands, and any manipulation of this device is globally affecting the shape of the model. In other words, the input device is itself our virtual object.
- ***Physically-based simulation:*** We integrate a plasticity model instead of a geometric method to compute the physical deformation of the virtual object. We use a transfer function that maps the gestures captured by the input device to the input of the physical model as boundary conditions, forces, or displacements.
- ***Interactive visualization:*** Naturally, in the real world, deforming an object simultaneously affects its geometry. To mimic this behavior, the deformation of the virtual object is visualized in real time when changes are made by the user.

Our contributions integrate objectives of the SeARCH project (Semi-automatic 3D Acquisition and Reassembly of Cultural Heritage). One objective of this project is to develop new interactive systems for cultural heritage professionals. At present, the manipulation of acquired virtual objects offers a high potential for archeological reasoning, , especially when the real objects are difficult to access.

One of the current concerns of the SeARCH project is the exploitation of intuitive tools that enable to study the suffered deformations of acquired 3D virtual objects by the application of forces on them. Archeologists can thus interactively validate or reject different deformation hypotheses. Indeed, this manipulation allows the archeologists to better understand the chronology of the different deformations of archeological findings and thus the retrieval of their original shapes. Our work is mainly focused on the manipulation and deformation of “staples” discovered at an archeological site in Alexandria in Egypt.

In this paper, we present a prototype that validates our approach for beam-shaped objects. This application has a high pedagogical value for teaching solid mechanics.

We experiment the potential of an input device called ShapeTape, an array of fiber optic sensors that is sensitive to bend and twist manipulations.

The remainder of this paper is structured as follows. We review previous work on deformation modeling in Section 2. Then, in Section 3, we describe the principal components of our tangible system for physically-based deformations. In Section 4, we detail our interaction model based on the ShapeTape manipulations. We suggest, in Section 5, some possible applications of our approach to education and archeology. Section 6 presents results of our

ESTIA, F-64210,Bidart, France.
LaBRI, INRIA, UMR 5800,F-33400,Talence, France.
Univ. Bordeaux Segalen, F-33067 Bordeaux, France.
[n.takouachet| n.couture| p.joyot| n.verdon| g.riviere]@estia.fr], [couture| preuter]@labri.fr].

process applied to beam deformations, before we conclude in Section 7.

2 Related Work

In the literature, a wide range of methods in the area of the deformation modeling have been proposed. They can be classified into two principal categories: physically-based methods and geometric ones.

Physically-based methods ensure an accurate simulation of the real-world behavior of objects, due to the direct integration of boundary conditions and physical material properties. The analytical solutions of partial differential equations (PDE) involved in mechanics can be very complex to obtain, and most of time impossible. To address this problem, numerical approaches like finite element (FE) modeling [17] are traditionally used, but they require a considerable amount of processing time, in particular when it comes to calculate large deformations for a complex geometry.

Martin et al. [12] have proposed a unified treatment based on generalized moving least squares (GMLS). The authors have combined in a single function the simulation of 3D elastic rods, shells, and solids, and they are able to calculate diverse elastic behaviors, including buckling, writhing, cutting and merging.

Even though the computational power allows more and more complex mechanical calculations, real-time simulations in the field of non-linear mechanics remain a challenging task. In order to increase the speed of computations, reductions order models (ROMs) have been intensively used in the past decade; in many areas such as fluid mechanics as well as solid mechanics [13].

On the other hand, geometric deformation methods are widely used in geometric modeling and 3D animation. Deformations are performed by directly modifying parameters of its geometry. An object represented by splines can be deformed by directly moving its control points. In contrast to physical methods, the computation incurs usually lower costs. Nevertheless, the major drawback of these methods is that they are unable to reproduce realistically physical deformations. In fact, they do not accurately take into account forces or even mechanical properties of the material.

A large family of geometric deformation methods exists. Among these works, we mention *Wires* [14], inspired by a technique used in sculpting. The principle is to characterize the geometry of the object roughly by a set of curves, and to create a region of influence around each curve. The modification of one or more curves induces a modification of the geometry, but at a higher computational cost. Zhou et *al*.[16] have presented a system that can handle large deformations of 2D curves by minimizing a quadratic energy function, by transferring the deformation to curves on a 3D mesh for solid deformation.

To date, most existing 2D/3D deformation systems are based on the WIMP paradigm [15]. To perform deformations, usually applied directly on the object by the appropriate tow-hand gestures, the user must express his actions in terms of complex geometric manipulations controlled by mouse/keyboard commands. To move beyond this limitation, much recent works in the research community are oriented to explore new ‘intelligent’ input devices through interactive techniques to provide easier and more intuitive user/computer dialogues. Tangible User Interfaces (TUIs) [1] [9] [10] are among the emerging approaches that are currently explored. The main idea is to allow the user to control the digital information via the direct manipulation of an object in the physical world, and so the user acts and interacts with the physical device in complete abstraction of the computer.

Ravin Balakrishnan et *al.*, [1] [7] use a tangible user interface for creating and editing curves and surfaces by manipulating a high degree-of-freedom ribbon called ShapeTape, thus exploiting the affordance of a physical device for manipulating virtual curves. However, their application was limited to handling only the geometry of curves and surface regardless of the underlying physics.

In our work, we attempt to exploit the affordance of the ShapeTape to control physically-based deformations of 3D shapes.

Llamas et *al.* [11] proposed a system of two-hand manipulation using two magnetic sensors to deform geometrically parts of tubular 3D objects. Lee and *al.* [8] have proposed *Isphere*, a bi-manual tangible interface for 3D geometrical deformation. The input interface is a hand-held dodecahedron. Each facet is designed as a capacitive electrode that detects the distance from the human body. This dodecahedron takes inputs from 12 capacitive sensors which control a virtual 3D model. Their system is limited to handle round shapes and therefore does not allow certain deformations such as bending or twisting.

Vincenzo Caglioti and *al*. [3] have proposed a tangible input device for 3D curves. The system is based on a piece of flexible wire and a single off-the-shelf photo camera. The resulting 2D curves are then extruded and combined to create more complex shapes. Again, this work is in the geometric modeling domain. Indeed, the proposed system can create complex objects by combining simple ones.

Last but not least, Robert Blanding and *al*. have developed ECAD [2], a Phantom-based haptic system which combines techniques of virtual reality (VR) with a real-time solver to calculate physically-based deformations. The user of the ECAD system interacts with the virtual model through various input devices such as the Phantom, 3D glasses, and a 3D mouse. For real-time computation, the authors suggest a simplification of the geometry of the 3D model.

3 INTERACTION SYSTEM

3.1 Overview

A tangible interface that integrates a mechanical solver for simulating physically-based deformations may be carried out according to the schematic diagram shown in Figure 1. It has three main components: the virtual 3D object, the input device and the physical solver.

The user controls the shape of the virtual object through the direct manipulation of the deformable input device. He applies forces on the input device, and actions are then triggered on the physical solver to simulate the mechanical behavior of the real object. The resulting deformations are then projected on the geometry of the virtual object and visualized on a computer display. This general process is running in a loop for simulating continuous deformations.

Nevertheless, the communication between these three main components is not directly established. Hence, we integrate three intermediate modules: 3DtoID, IDtoPM and PMto3D.

Initially, the virtual object has to be linked with the input device; since the form of the input device generally differs from

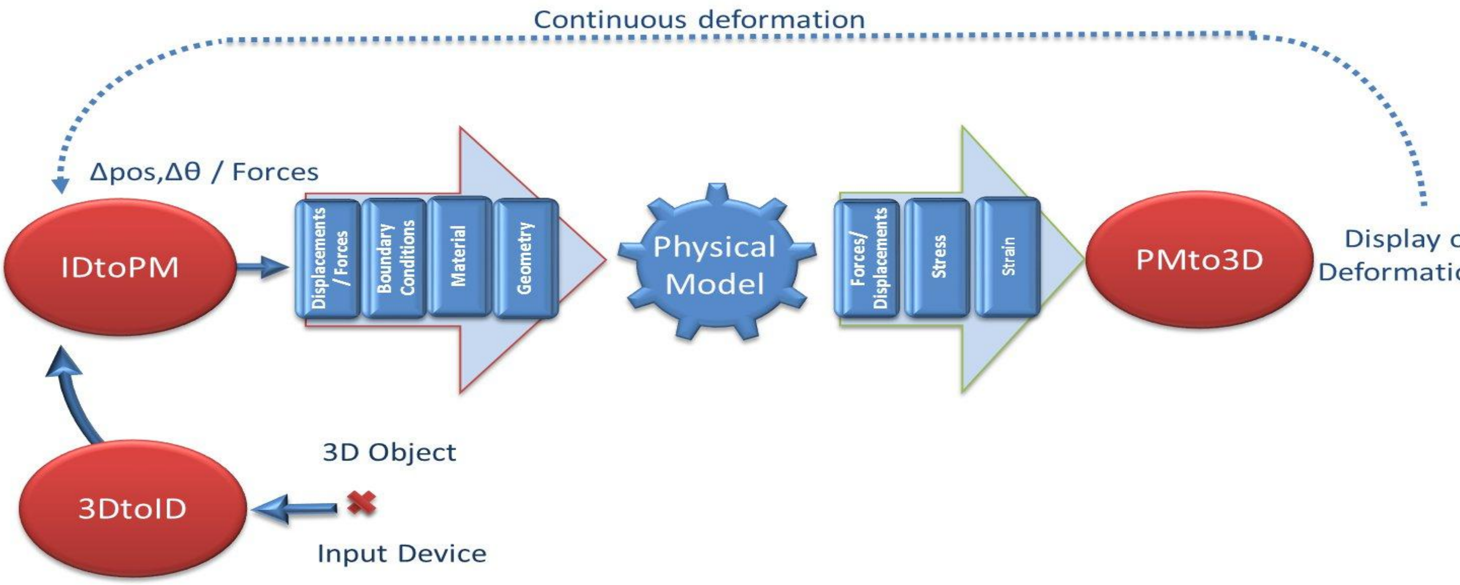

Figure 1. A general schematic representation of tangible system for physically-based deformations

the object. Therefore, we use the module *3DtoID* to embody the object geometry in the input device. The input device is indeed a set of sensitive points, each one is linked to one or more points of the object, thus allowing a global control of its shape. The details of the implementation of this module in our specific application are given below.

To activate the simulation, the actions performed by the user on the input device and thus the virtual 3D object must be mathematically formulated by the module *IDtoPM*, in terms of the appropriate input of the physical solver.

Finally, the results of the simulation must be treated by the module PMto3D in order to extract the useful information to be displayed.

We developed a prototype framework that meets this system architecture. The first difficulty, inherent in the metaphor of the tangible interaction, is linked to the choice of the possible interaction modes between the user and the deformable input device and their mapping to virtual interactions.

In addition, the inclusion of a mechanical solver involves additional difficulties and opens the question of how virtual actions have to be expressed to give inputs to the physical computation.

To address step-by-step the mentioned problems, we integrate in a first stage a linear physical solver that handles small deformations, and we limit our process to pilot beam deformations. We exploit the natural affordance of the malleable sensitive beam known as the ShapeTape and described in the following section. The intuitive bi-handed user manipulations induce naturel bend and twist deformations.

3.2 Input Device: ShapeTape

The ShapeTape is an array of fiber optic sensors fixed on a thin malleable strip of metal, enveloped in a plastic coating for protection. One of its ends is attached to the fiber optic light source and the USB connection to computer. The sensitive zone is delimited by two colored bands; it contains 16 sensors arranged in 8 pairs. The model that we use is a (32x 1 x 0.1) cm dimensions.

A bend and twist of the sensitive parts of the tape modulates light through the fibers. The locations of the variations in light intensity are captured and used to calculate 6DOF (six-degree-of-freedom) Cartesian data (x, y, z, roll, pitch, and yaw) for each segment of the strip. This data can be interactively used for constructing a 3D model that closely reproduces the form taken by the tape.

There are two main raisons why we use the ShapeTape as the principal input peripheral for controlling the user interactions over our system: First, this device is beam-shaped; naturally it leads the user to employ his fingers and hands to bend and twist it. Second, it allows an interactive control due to the high-speed data acquisition from sensors.

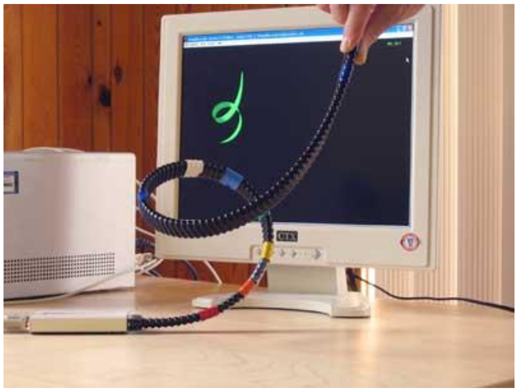

Figure 2. The ShapeTape used as an input device for piloting its 3D virtual copy.

3.3 Physical Model

The originality of our approach consists in taking into account the mechanical behavior of the studied object. For the example of the deformable beam, the problem is well-posed when boundary conditions, geometry and material properties are given. In mechanics, boundary conditions specify the conditions that are imposed to the boundary of the object, for instance it can be fixed at one extremity or submitted to a given force.

The result of a solid mechanics computation can be obtained in terms of force values or displacements, depending on the formulation we choose for the boundary conditions. Indeed, if we consider as input a given force, the result will be the displacements of all the points in the beam. In the same way, if the input is the displacement, then the result will be the corresponding force.

For example, we consider the beam fixed at its left extremity (x=0) and submitted to the force F at its right end as depicted in Figure 4.

The analytic solution that describes the displacement of the beam is given by the following equation:

$$u_2 = \frac{x-L}{6}^{3} - \frac{L^2}{2}x + \frac{L^3}{6}\ \alpha \qquad (1)$$

Where u_2 is the y-displacement at a given x location in the beam and L its length. $\alpha = \frac{F}{E\,I_z}$, E is the Young modulus of the material and Iz is the inertial moment of the beam (that depends on the geometric form of its section).

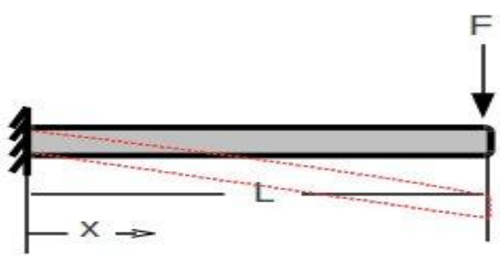

Figure 3. A beam fixed at its left extremity and submitted to a vertical force.

4 THE PROPOSED INTERACTION METAPHOR

As already explained, when we provide displacements to the input of the physical model, the latter calculates the acting force and vice versa. On the other hand, the ShapeTape provides just the displacements (coordinates) from each point of sensors. Hence it is obvious that if we use these displacements, the physical solver computes only the applied force. Furthermore, in addition to the force value, we have to calculate the new displacements from the physical simulation, since they are required for displaying the deforming virtual object.

At this stage, a problem arises from this methodology: how can we compute simultaneously both the force and the new displacements to simulate the example of the beam shown in Figure 3, we first capture the movement of the ShapeTape's endpoint. We randomly choose a reference material (e.g. steel). The two are then inserted into the mechanical solver for calculating the associated force, and so the force exerted by the user can be quantified. To perform the physical simulation of the deformation, we introduce afterwards the real material of the beam (Young's modulus, see Equation 1). The simulation of the deformation depends on the force indicated by the displacement of the ShapeTape and the characteristics of the real material. The result of this simulation is the actual displacement associated to each point of the geometry of the virtual beam.

5 TARGETED APPLICATIONS

In this paper, we aim to offer an educational tool that should help *professors and students to* understand and illustrate mechanical phenomena. We are particularly interested in physically-based beam deformations, since it is most common in solid mechanics to rely on the beam theory [4] [5] [6] to study strength of materials and deformations provoked by the acting forces.

We believe that this approach is also largely applicable in historical and archaeological analysis. Instead of using complex CAD (*Compter Aided Design*) software, archaeologists can directly control shapes of deformable archaeological artifacts by means of manipulations that they are familiar with. Thus, the cognitive load of the archaeologist can be fully devoted to the main task: reflections and analysis rather than understanding and adapting the complex functionalities and interaction metaphors of the system.

Figure 4. A deformed staple discovered on the archaeological site of the Pharos of Alexandria.

The Centre d'Études Alexandrines (CEAlex), founded in 1990, aims at the studying and saving of Alexandria's archaeological heritage. One of the current topics concerns the construction and the history of the Pharos Lighthouse, one of the Seven Wonders of the Ancient World.

The group is conducting underwater archaeological excavations of the ancient Pharos. Some of the larger blocks of granite that have been found seem to stem from the pharos building. These blocks are held together with iron "staples". An inset in the shape of the staple was carved horizontally into the surface of two adjoining blocks, across the abutment, one end in one block and the other end in the other. With the staple in the shaped recess, the next tier of blocks holds the staple in place.

It is practically impossible to manipulate manually these huge blocks. This is why 3D computer modeling is an alternative solution that allows the user to manipulate virtually a 3D model of the archaeological artifact. Recently, researchers from CEAlex used photogrammetry in order to reconstruct a faithful 3D geometry of the real objects.

One of the discovered staples is distorted. As depicted in Figure 4, the deformation is mainly due to a bending of the base to the inside. However, according to the architectural principles of

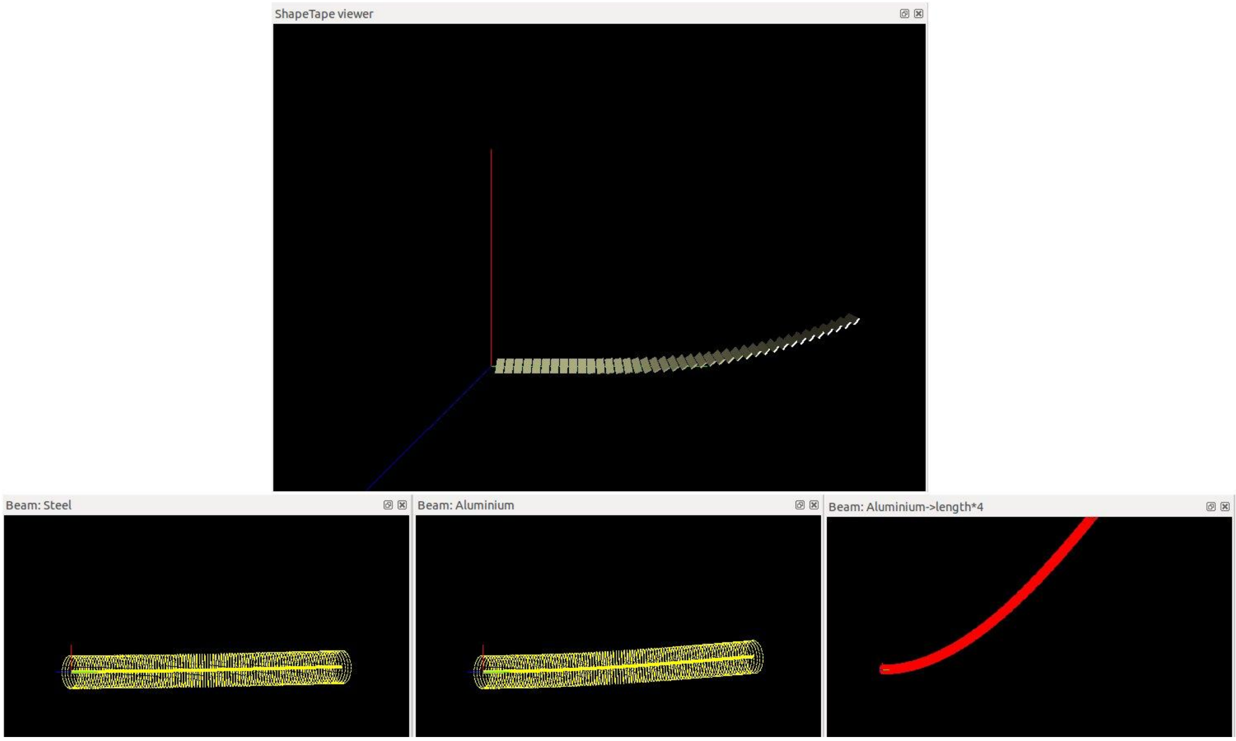

Figure 5. Beam physically-based deformations controlled interactively by the ShapeTape. For the same ShapeTape displacement, the mechanical behavior of the beam changes according to the characteristics of the material (steel, Aluminum) and the length.

the Alexandria's Pharos period, the base (the central part) of such staples must be horizontally right.

This metal staple seems to belong to one of the columns that held the plateau of the lighthouse over the water. Understanding the events that have caused the flexion of this staple may highly contribute to the construction of the history of the Pharos, and may even indicate the real reasons of its final collapse.

Our approach might be used to address this issue, since the staple can be considered as a beam that was folded at both ends. The archaeologist performs deformations directly with the ShapeTape, he thus applies forces to the virtual model of a supposed original form of the staple. By successive iterations, the deformed model is then compared to the staple from the excavations. This favors reflections of the archaeologist and helps to validate the hypothesis that he investigates.

6 Experimentations

In a first stage of the application of our process to the deformation of archeological “staples”, we validate our approach for the simulation of beam deformations.

In the case of small deformations, the beam is represented by its medial axis. Hence, we perform a simple point by point mapping to link the ShapeTape to the geometry of the virtual beam.

As shown in Figure 5, for a given displacement of the ShapeTape, the behavior of the beam changes according to the type of the material and its dimensions. Indeed, under a bending action, an Aluminum beam *(Young's modulus= 69E+9*) moves more than a steel one *(Young's modulus= 210E+9)*. As well, an Aluminum beam four times longer bends even more.

The resistance of the material is given by the stress value. When the strength of the material becomes less than the applied force, this means that the object is broken. This state is represented by a red coloration, like for the long beam in Aluminum shown in the left part of Figure 5.

7 Conclusion

We proposed a tangible user interface for physically-based deformations. We incorporate a mechanical solver for taking into account the physical behavior of metallic objects under acting forces.

We exploit the affordance of the ShapeTape for a natural bending and twisting based on two-handed input. The user applies forces directly on the tape, and the gestures are then formulated in terms of the input of the mechanical solver.

This paradigm promises various applications in different domains. Our current work is mainly dedicated to archaeological applications. The objective is to help archaeologists for understanding the events of “staples” deformations and for validating historical hypotheses.

The work we have presented in the paper is the validation step of our approach for simple beam-shaped objects. It shows its feasibility for more complicated geometries such as the archeological “staples” and to handle other types of deformation such as traction or shear. In addition, this application offers an interactive educational alternative to illustrate and explain easily the strength of materials based on the beam theory.

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