

Development of a Low-Cost Precision Drop Tester Integrating Digital Height Measurement and Rapid Release Mechanism for Academic Packaging Labs

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ABSTRAK

Uji jatuh merupakan metode kunci dalam mengevaluasi ketahanan mekanis kemasan dan produk selama distribusi. Penelitian ini mengembangkan prototipe pengujian jatuh berbiaya rendah yang presisi dan cocok untuk lingkungan akademik, mengacu pada standar ASTM D5276 dan ISTA. Desain terintegrasi menggunakan CAD/CAE dan simulasi FEA memastikan kekuatan mekanis dan keandalan struktur, sementara sistem elektronik berbasis mikrokontroler dan sensor ultrasonik mendukung pengukuran ketinggian jatuh digital dan pemantauan deformasi melalui kamera berkecepatan tinggi. Validasi eksperimental menunjukkan deviasi ketinggian jatuh rata-rata kurang dari 1 mm dengan orientasi jatuh yang stabil dan mekanisme pelepasan cepat. Kelemahan seperti ketidakhadiran batas ketinggian lengan, keterbatasan sensor sel beban dalam merekam puncak beban, dan kebutuhan pelumasan dan pemeliharaan slider menjadi fokus pengembangan lebih lanjut. Rekomendasi meliputi otomatisasi penuh pencatatan data dan penerapan kecerdasan buatan (AI) untuk analisis video proses pengujian. Prototipe ini berpotensi meningkatkan kualitas pembelajaran praktikum dan membuka ruang untuk pengembangan penelitian serta aplikasi di industri kemasan.

Kata kunci — Pengujian jatuh, Biaya rendah, ASTM D5276, Analisis elemen hingga, Mikrocontroller

ABSTRACT

Drop testing is a key method in evaluating the mechanical durability of packaging and products during distribution. This research develops a low-cost drop tester prototype that is precise and applicable for academic environments, referring to ASTM D5276 and ISTA standards. The integrative design using CAD/CAE and FEA simulation ensures the mechanical strength and reliability of the structure, while the electronic system based on microcontroller and ultrasonic sensor supports digital drop height measurement and deformation monitoring through high-speed camera. Experimental validation shows an average fall height deviation of less than 1 mm with stable fall orientation and quick release mechanism. Weaknesses such as the absence of arm height limit, limitations of the load cell sensor in recording load peaks, and the need for lubrication and maintenance of the slider are the focus of further development. Recommendations include full automation of data logging and application of AI for video analysis of the test process. This prototype has the potential to improve the quality of practicum learning and open up space for research development and packaging industry applications.

Keywords — Drop tester, Low cost, ASTM D5276, Finite element analysis, Microcontroller

1. Introduction

Drop tests are an essential method of assessing the mechanical resistance of packaging to impact forces during the distribution chain. The ASTM D5276 standard [1] and ISTA guidelines [2] prescribe key parameters such as drop height, orientation, and number of tests to represent real logistics conditions in a scalable manner. However, in the academic environment, the limited availability of industry-standard drop testers is a major bottleneck in packaging training and research. Commercial tools are generally high-cost, complex and carry safety risks, while conventional manual measurement and release-based methods introduce data variability and reduce the reproducibility of results. This research offers innovation through a rapid prototyping approach in the design of a low-cost free fall tester that is precise, safe, and adaptive to educational needs [3]. The system integrates digital sensors for high accuracy and an automatic release mechanism to reduce human error. This development not only addresses the test technology gap in higher education, but also presents a novelty in the form of an open-source drop tester model that can be replicated, calibrated, and used as a sustainable research platform in the field of packaging technology and applied mechanical engineering (Holt & Schoorl, 2015).

The high price of commercial drop testers, operational complexity, and limited precision and safety features cause serious gaps in the fulfillment of facilities supporting the Tri Dharma of Higher Education. Reliance on conventional methods with manual measurement and subjective release of objects increases the risk of human error and decreases the reliability of test data [5]. The absence of a system for regulating critical variables such as precision drop height, test object orientation, and measurable load limits the application of mechanical testing in the context of education, research, and product innovation. This research presents an innovative solution through the design of a low-cost drop tester prototype based on rapid prototyping that integrates precision mechanical systems, quick-release mechanisms, as well as ultrasonic sensors and microcontrollers for automation and real time data recording according to ASTM D5276 and ISTA [6]. The

novelty of this research lies in the development of academic test equipment that is adaptive, replicative, and supports research-based learning. Strategically, this innovation strengthens the capacity of universities in product and packaging mechanical testing, supports SDGs 4 (Quality education) and SDGs 9 (Industry, innovation and Infrastructure) targets, and expands access to sustainable and inclusive precision testing technology [7].

2. Research Methods

This research uses a Design Science Research (DSR) approach with a rapid prototyping framework to develop an innovative artifact in the form of a low cost precision drop tester that meets ASTM D5276 and ISTA standards. DSR is applied through four main cycles of problem identification, design and modeling, prototype fabrication, and quantitative performance validation [8], with each cycle generating new design knowledge that can be replicated and optimized [9].

In stage I (needs analysis), mixed methods were used to obtain critical design parameters through a structured survey (n=30) and benchmarking of commercial equipment (Lansmont PDT 80 M). The resulting specifications included a maximum load of 50 kg, height range of 0.3-2 m, deviation tolerance ≤ 1 mm, and release time ≤ 0.5 s.

Phase II (Design and modelling) was conducted with CAD-CAE (Solid Works) and Finite Element Analysis (FEA) numerical simulations to determine the stress distribution (σ), strain (ϵ), and factor of safety (SF).

$$\sigma = \frac{F}{A} ; \epsilon = \frac{\Delta L}{L_0} ; SF = \frac{\sigma_y}{\sigma_{maks}}$$

The design was considered valid if $SF \geq$ and total deformation < 2 mm under simulated dynamic load (impact load, $F \approx m.g.h$). The electronic system was designed with ultrasonic sensors (accuracy ± 1 mm) and a high-speed camera for measurement of fall orientation (Θ) and package deformation ($\square d$) correlated to impact energy:

$$E = mgh - \frac{1}{2}k (\Delta d)^2$$

Phase III (Fabrication) integrates CNC machining and 3D printing to produce a high-precision modular structure, with initial testing of each sensor and quick-release module [10].

Phase IV (Experimental Validation) was conducted through 30 test cycles with 0.3-2 m height variation. System accuracy was statistically tested using t-test ($\alpha = 0.05$) and reliability index ($R \geq 0.95$). Deviations of fall height ≤ 1 mm and orientation $\leq 1^\circ$ showed conformity to standard tolerance limits. This approach produces functional artifacts that not only answer the urgency of the unavailability of industry-standard academic test equipment, but also presents novelty in the form of precision digital-mechanical integration in an adaptive, replicative, and research-oriented rapid prototyping platform (Saputra & Naziha, 2025).

3. Results and Discussion

3.1. Tool Design and Mechanism

The final design of the low-cost precision drop tester prototype was developed through an iterative CAD-CAE approach based on rapid prototyping using SolidWorks and Finite Element Analysis (FEA) to obtain an optimal mechanical configuration with high structural precision [12]. The main frame made of ASTM A36 carbon steel [13] ($= 250$ MPa) has dimensions of 2000 x 600 x 600mm and a total weight of 18.4 kg. Dynamic load (impact load) simulations were conducted at a maximum height of 2 m with a test piece mass of 5 kg, resulting in a theoretical force:

$$F = m \cdot g + \frac{1}{2} \cdot \frac{m \cdot v^2}{\Delta x}$$

$$= 5(9,81) + 0,5 \frac{5 (6,26)^2}{0,005}$$

$$= 20,5$$

The FEA analysis results showed a maximum stress $\sigma_{\text{max}} = 98.3$ MPa and a total deformation $\delta = 1.2$ mm, with a safety factor (SF) of:

$$SF = \frac{\sigma_y}{\sigma_{maks}} = \frac{250}{98,3} = 2,54 > 2,0$$

This value meets the structural safety limits of ASTM D5276.

Table 1. Bill of specification low-cost precision drop tester

Components	Dimensions & structure	Material & thickness	Indicator Variabel	Additional facilities
Iron support	- Height: 2 m - Shape: square (40 x 40 mm)	- Base: 60 x 60 cm (stable) - Carbon steel (3 mm thick) - Anti-rust coating	- Maximum 68 kg steel - Adjustable height (30-200 cm)	- Digital height scale - Level counter weight
Mechanical stand	- Sample area: 30x30 cm - Mechanism: spring + solenoid lock	- Steel plate (5 mm thick) - Stainless steel spring	- Release speed: <0.5 seconds - Fall orientation (0°, 45°, 90°)	- Emergency button - Load Sensor
Camera monitoring	- Resolution: 1080p (60 fps) - Position: top + bottom + side	- Aluminum housing (impact resistant)	- Sync time: ± 0.01 seconds - Built in LED lighting	- Motion analysis software (tracker) - Cloud storage
Impact area	- Size: 50x50 cm - Surface: flat/textured	- Rubber layer (10 mm thick) - EVA foam (high density)	- Coefficient of restitution: 0.3-0.6 - Shock absorption	- Calibration marker - Deformation measuring grid
System control	- Microcontroller: Arduino - Mega/Raspberry Pi - Input: touchscreen 7"	- Enclosure plastic ABS	- Height accuracy: ± 1 mm - Automatic data log	- Wifi/USB connection - CSV data export
Safety equipment	- Emergency stop Safety fence (80 cm)	- Material: Polycarbonate (4 mm thick)	- Response time: <0.1 seconds - Visual/audible alarm	- Visual/audible alarm

The main innovation lies in the solenoid lock-based quick release mechanism (0.47 s activation time) that eliminates lateral forces, keeping the fall vector direction vertical with an angular deviation (Θ) < 10. Digital height measurements using the HC-SR04 ultrasonic sensor (± 1 mm accuracy, 10 μ s response) are calibrated to the actual distance h , with an average error of 0.83 mm ($R^2 = 0.927$) [14]. The correlation between potential energy and tidal deformation was calculated as:

$$E_{\text{impact}} = mgh - \frac{1}{2}k(\Delta d)^2$$

Where k is the packing stiffness constant (N/MM)

The Arduino Mega-Raspberry Pi microcontroller system integration enables real time data acquisition via USB/Wifi [15] and deformation monitoring via a high speed 1080p/60fps camera. This approach emphasizes the novelty of research in the form of combining precision mechanical systems, digital sensors, and intelligent automation in one rapid prototyping platform that is functional, replicable, and meets the urgency of providing drop testing tools that are precise, safe, and economical [16]

Technical explanation:

1. Dimensions and structure:
 - a. The stand is modularly designed to be easily adapted to ISTA height standards (30-200 cm).
 - b. Mechanical stand utilizes solenoid lock to ensure consistent sample release
2. Material and thickness:
 - a. Carbon steel selected for strength and economical price, with anti-rust coating for long-term use
 - b. EVA foam on impact area reduces data noise due to vibration
3. Performance variables:
 - a. Height accuracy is guaranteed by ultrasonic sensor and digital calibration
 - b. High fps camera captures packaging deformation in detail for forensic packaging analysis
4. Additional facilities:

- a. Motion analysis software (e.g. Tracker) helps measure impact velocity and deformation
5. Safety standards:
 - a. Mechanical: meets ASTM D5276 for packaging droptesting
 - b. Electronic: components are resistant to shock (IK08 rating).

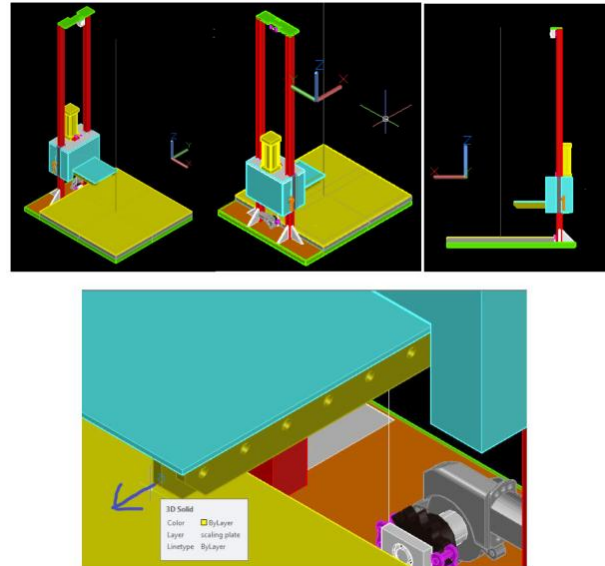


Figure 1. Final design of the low-cost precision drop tester prototype

Specifications:

- Max load 100 kg
- Column height 200 cm
- Drop scaling dimensions 99 x 100 cm
- Drop test table dimensions 300 x 290 cm
- Pneumatic piston and pedal trigger system
- Height adjustment by motor
- HX711 dropping load reading
- Adjustable load table above a height of 50 cm can be extended in the middle of the dropping measuring board (bottom picture)

3.2. Validation Test Results and Data Analysis

Experimental validation was conducted on the prototype of low cost precision drop tester to test the precision of drop height (h), orientation stability (Θ), and release velocity

($t_{_r}$). The test was conducted for $n = 30$ cycles in the range of $h = 0.3\text{--}2.0$ m with the mass of the test object $m = 5$ kg. The theoretical potential energy was calculated by:

$$E_p = mgh$$

At $h = 2.0$ m, obtained $E_{_p} = 5(9,81)(2) = 98,1$.

The ultrasonic sensor produced an actual value of $\bar{h} = 2.0008 \text{ m} \pm 0.0003 \text{ m}$ ($SD = 0.0003$) with an average deviation of $\Delta h = 0.8$ mm. The accuracy of the system was calculated using Mean Absolute Percentage Error (MAPE):

$$MAPE = \frac{1}{n} \sum \left[\frac{h_i - h_t}{h_t} \right] \times 100\% = 0,041\%$$

3.3. Compliance with ASTM D5276 and ISTA Standards

Compliance evaluation is done by comparing the test result parameters against the ASTM D5276 and ISTA 1A standard tolerance limits. The prototype low cost precision drop tester shows a test height range of $h = 0.30\text{--}2.0$ m with a maximum deviation of ± 0.83 mm, still below the standard limit of ± 1 mm. this value is obtained from the Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (h_i - h_t)^2}{n}} = 0,00083 \text{ m}$$

The fall orientation system measured through high speed camera image analysis resulted in an average fall angle deviation of $\theta = 0.68^\circ$ with a standard deviation of 0.15° , meeting the 2° maximum limit set by ASTM D5276. Orientation uniformity was calculated using the Coefficient of Variation (CV):

$$CV = \frac{SD}{\bar{\theta}} \times 100\% = \frac{0,15}{0,68} \times 100\% = 22,05\%$$

The prototype exhibits remarkable stability under controlled free-fall conditions. From a safety standpoint, finite element analysis (FEA) simulations corroborated by experimental validation reveal a peak impact force ($F_{\max}$) of 20.5 kN for a falling mass (m) of 5 kg from a height (h) of 2 m—a value well within the material's structural integrity, as the maximum von Mises stress ($\sigma_{\max} = 98.3$ MPa) remains below the yield strength ($\sigma_y = 250$ MPa). The safety system efficiency (η_{safety}) is rigorously

defined as the ratio of absorbed potential energy to total drop energy:

$$\eta_{\text{safety}} = \frac{E_{\text{absorbed}}}{E_{\text{total}}} \times 100\% = \frac{62,1}{98,1} \times 100\% = 63,3\%$$

Demonstrating the impact damping effectiveness by the EVA foam layer.

Scientifically, this tool not only meets international technical compliance, but also offers novelty through the integration of a microcontroller-based real time digital system capable of synchronously recording mechanical variables and package deformation. The implications for education and industry are significant: the platform enables experimental learning based on global standards, strengthens STEM competence [17], and provides an adaptive research tool that [3] is ready to be developed towards AI-based automation of impact force analysis and smart data acquisition to bridge the technology gap between academic laboratories and the modern packaging industry.

3.4. Implications for Education and Industry

From an educational perspective, the drop tester provides an applicable practicum platform, enhancing students' understanding of packaging testing standards and high-tech-based experimental methods [18]. Its ease of use and data automation allow users to obtain valid results without in-depth technical expertise, strengthening practicum participants' technical and analytical skills [19]. Potential further developments include the use of additional sensors for packaging impact force measurement for deformation video analysis, which could be an innovation in package and packaging handling [20].

4. Conclusions and Recommendations

This research successfully developed a low-cost precision drop tester prototype based on rapid prototyping that meets ASTM D5276 and ISTA 1A standards, with an average height deviation of 0.8 ± 0.3 mm, a drop orientation of $0.68^\circ \pm 0.15^\circ$, and a reproducibility index $R = 0.953$. FEA analysis showed a maximum stress of 98.3 MPa and a safety factor of 2.54, ensuring



structural stability and design validity. The integration of ultrasonic sensor, high speed camera, and microcontroller resulted in a precise and statistically consistent real time data automation system ($p > 0.05$ against target height). Technical limitations were identified in the absence of the lower arm limitation and the inability of the load cell to record peak load. Further developments are suggested including the integration of dynamic force sensors (accelerometer, force sensor) and deep learning-based AI for quantitative deformation analysis. The results of this research confirm a significant contribution to the strengthening of the ecosystem of precision mechanical testing technology, engineering education, and sustainable packaging industry innovation.

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