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Physics-Based Approaches to Simulating Dynamic Phenomena in Containers for Sensitive Cargo

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This article presents a simulation-based analysis of the dynamic phenomena that occur during the transportation of sensitive cargo in containers. A key element of the studied structures is an internal vibration–isolation system consisting of wire-rope isolators. Each isolator is constructed from two bars connected by a stainless steel wire rope, forming a horizontal spring with nonlinear elastic-damping properties. The dynamic problem with impulsive excitation focuses on kinetic energy transfer and vibration-damping characteristics as critical factors. Multi-body simulation in SolidWorks Motion is compared with finite element analysis using LS-Dyna software, which enables the description of high-energy transient phenomena such as collisions and explosions. The adopted numerical models reveal key differences and inform the appropriate method selection. The paper examines how overloads are transferred to the cargo when a container model is dropped from a specified height. The resultant displacement of the inner frame for both analyzed models is nearly identical, reaching a maximum spring deflection of 0.03 m. Static equilibrium occurs at 0.04 m and 0.05 m for SolidWorks Motion and LS-Dyna, respectively. The results enable the formulation of design guidelines for transport containers aimed at minimizing the risk of cargo damage by optimizing dynamic characteristics and ensuring proper cargo distribution within the structures.

topics: drop test, dynamic phenomena, shock isolation, shipping container

1. Introduction

The drop test of shipping containers is a critical evaluation method used to ensure the structural integrity and durability of containers under real-world handling conditions. During transportation and logistics operations, containers are often subjected to accidental drops, impacts, and rough handling, which can compromise their ability to protect the goods inside [1, 2]. By performing drop tests, engineers and researchers can assess the container's ability to withstand such forces, identify potential failure points, and validate design improvements. These tests are crucial to ensuring safety, minimizing cargo damage, and maintaining compliance with industry standards and regulations [3–8]. Physical drop test, although essential for assessing durability and performance, has several drawbacks, including high cost, the requirement for a properly equipped test stand, the risk of damage to both the testing equipment and the tested structure, limited insight into internal mechanics, safety concerns, and the difficulty of testing extreme conditions.

A study of the current knowledge on shipping container drop tests revealed a gap in the analysis of structures, including the internal isolation system that protects the transported cargo. The vast majority of scientific publications related to drop test terminology focus on studying the resistance of household appliances to shock waves induced by impact loads [9]. Some publications address drop tests of steel sheet containers for the final disposal of nuclear waste [10] or other goods [11, 12]; however, these structures do not contain internal shock isolation systems. The outcomes of the review of publications reveal a gap in research dedicated to specially designed shipping containers with internal shock isolation systems for transporting sensitive objects such as aircraft engine modules, advanced laboratory equipment, or medical devices. The results presented in this article provide insight into the modeling approach for shipping containers subjected to impact loads induced by gravity. This fills the gap in current knowledge regarding modeling methods, comparison of results, and recommendations for eliminating physical drop tests.

This paper provides a basic understanding of the mechanical principles of drop test and a modeling approach for simulating impact phenomena using the commercial codes SolidWorks Motion and Ansys LS-Dyna. Of the many possible drop test configurations described in international standards related to the transportation domain, two specific cases have been selected for detailed computational modeling, namely face drop and corner drop.

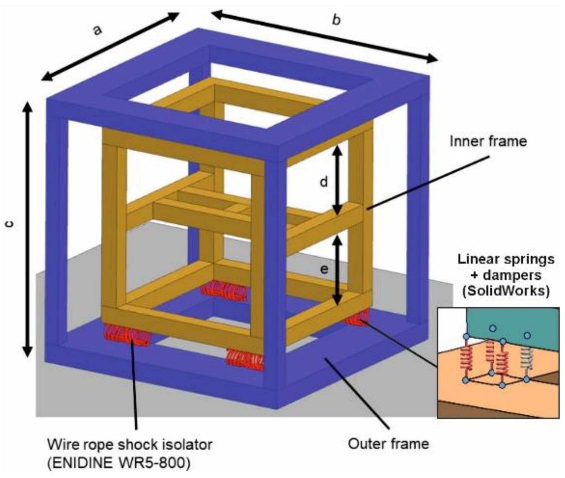

Fig. 1. Geometry of shipping container subjected to drop test simulation.

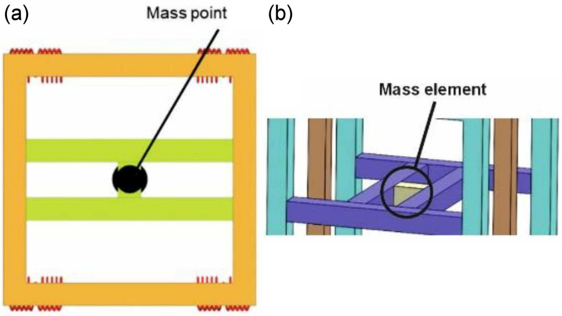

Fig. 2. Mass point location on the inner frame: (a) Ansys LS-Dyna, (b) SolidWorks Motion.

The primary objective of this work is to evaluate the approach and feasibility of modeling a drop test in a virtual environment, rather than performing a laboratory test [13]. The detailed analysis of the results, including a comparative study of simulation software and the methodological approach, provides a solid foundation for developing design guidelines applicable to private-sector companies.

The conclusions presented in this paper determine whether virtual drop testing of shipping containers (designed for transporting sensitive cargo) has the potential to replace physical testing campaigns [14] and reduce the overall cost of commercializing this type of object.

2. Methods and materials

The computational modeling of the drop test study for specially designed shipping containers has been carried out using two commercial codes, i.e., SolidWorks Motion and Ansys LS-Dyna. LS-Dyna is well known among the simulation engineering community for analyzing rapid change phenomena, such as drop tests. The author's intent was also to evaluate SolidWorks Motion's ability to simulate the container drop test.

2.1. Model description

The simplified shipping container (Fig. 1) consists of an outer and inner frame connected by wire rope isolators (LS-Dyna) [15] or linear spring-damper systems (SolidWorks Motion). Overall dimensions are $a = b = c = 0.7$ m. The adjustable structure is located at mid-height of the internal frame ($d = e$).

The assumed weights of the outer frame and inner frame are 60 kg and 25 kg, respectively. Additionally, a mass point (LS-Dyna) or a solid element (SolidWorks Motion) of a mass of 55 kg is attached to the inner frame at the central point, as shown in Fig. 2.

The external and internal frames were modeled as S235JR structural steel (EN 10025-2:2004), with the following properties: $E = 207$ GPa, $\nu = 0.3$, yield strength $= 235$ MPa, density for the inner frame $= 1761$ kg/m^3, and for the outer frame $= 2210$ kg/m^3. The densities were adjusted to achieve the target frame masses.

A linear elastic model was used because the expected stresses remained below the yield point and to reduce computation time.

2.2. Load cases

Designing and certifying transport containers for delicate cargo should adhere to international industry standards to ensure quality, regulatory compliance, and compatibility across global transportation systems. Mentioned standards specify drop test configurations to be considered for container certification.

The performed simulations focus on two configurations, i.e., face drop (Fig. 3a) and corner drop (Fig. 3b).

In the face-drop scenario, the container is released from a height drop (h_{drop}) of 0.2 m onto its bottom face, reaching a velocity of 1.98 m/s at impact. With the impact force distributed over a large area, the risk of localized plastic deformation is minimal. Assuming ideal conditions (parallel orientation), no rotation is expected at the point of contact. Attention should be given to the closure of the shock isolators, which could induce additional shockwaves and rebound. Due to its simplicity, a face drop was simulated using SolidWorks Motion and Ansys LS-Dyna.

In the corner-drop case, the container is released from $h_{\text{drop}} = 0.150$ m, impacting a corner at 1.72 m/s. The impact on a rigid surface creates a real risk of localized plastic deformation and structural damage if the energy is not effectively absorbed or dissipated. The location of the center of

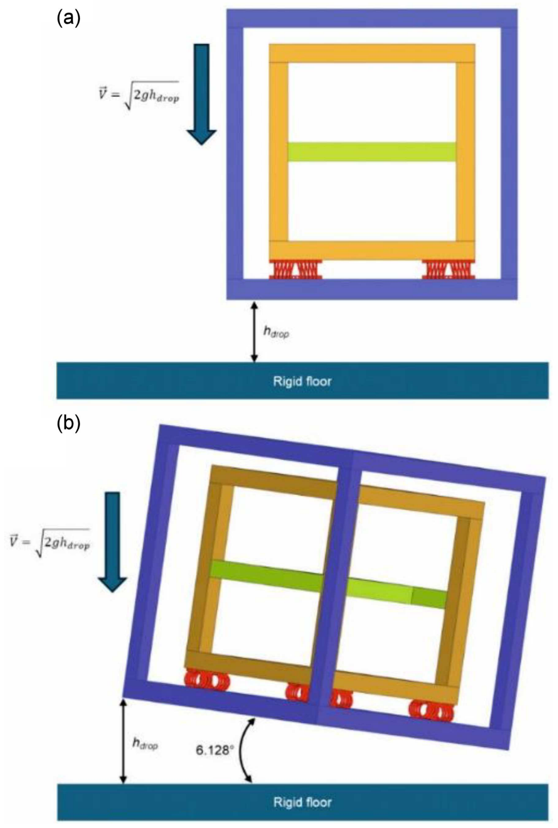

Fig. 3. Analyzed drop test schemes: (a) face drop, (b) corner drop.

gravity significantly influences the behavior of the entire structure by generating additional moment of inertia, causing the structure to rotate. The impact force components compress the springs along all three axes of the adopted coordinate system. This is related to different spring stiffness depending on the load direction. Due to the modeling complexity and SolidWorks Motion's limitations to single/torsional springs, this scenario was simulated only in Ansys LS-Dyna using its explicit solver.

3. Results and discussion

This chapter presents the results obtained using two commercial programs, i.e., Ansys LS-Dyna and SolidWorks Motion.

3.1. SolidWorks Motion

In SolidWorks Motion, all elements are treated as rigid bodies; therefore, velocities, accelerations, and reaction forces can be determined, but the material elasticity and deformation are not analyzed.

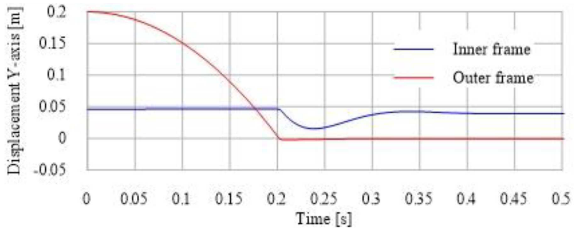

Fig. 4. Displacement in the Y-axis.

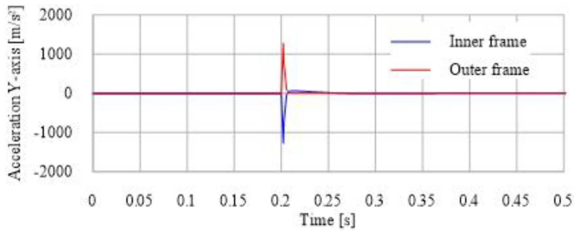

Fig. 5. Acceleration in the Y-axis.

The wire rope shock isolator (Enidine WR5-800) cannot be modeled as a geometric element, so its deflection cannot be verified classically. In this study, the isolator was represented by four linear spring dampers (Fig. 1). The combined spring stiffness equals the isolator's compression stiffness. It was assumed that for each individual spring, one has a spring constant of 9200 N/m and a damping constant of 276 N s/m.

Because linear springs cannot represent transverse stiffness (shear/roll), only the face-drop case was analyzed in SolidWorks Motion. The model assumes a steel structure impacting a steel ground. SolidWorks Motion defines stiffness and damping values for the force contact. In addition, it sets the penetration value to 0.0001 m, at which maximum damping is applied.

Figures 4 and 5 illustrate, respectively, the displacements and accelerations of the outer frame relative to the ground and of the inner frame relative to the outer frame, and specifically the changes in spring length.

With the assumed inputs, ground contact occurs at 2 s, generating very high accelerations in both frames. The linear springs do not close (the length remains greater than 0), and their motion is rapidly damped. The maximum spring deflection is about 0.03 m, while static equilibrium of the cargo occurs at a spring height of about 0.04 m (the initial length is 0.046 m).

3.2. Ansys LS-Dyna

In Ansys LS-Dyna, the model is already in contact with the ground, with the initial conditions set to represent a face- or corner-drop scenario. The

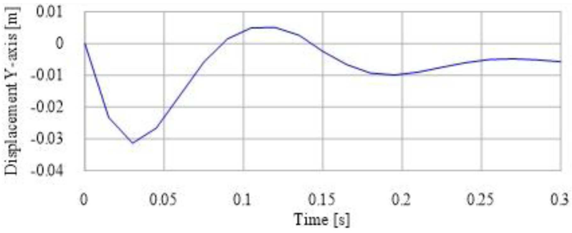

Fig. 6. Inner frame displacement under face-drop conditions.

maximum time step used in the simulation is based on the mesh size and equals 9.41×10^{-7} s. The model is meshed using the SOLID185 linear element type, which has a hexahedral shape with eight nodes at the corners and 3 degrees of freedom — translations in the X, Y, and Z directions.

The model utilizes mesh elements with sizes ranging from 10 to 20 mm; in total, 9095 elements defined by 15876 nodes were generated. Element quality check indicates:

- average aspect ratio of 1.4,
- average Jacobian (based on MAPDL method) of 1.009,
- average skewness of 0.0153.

Since the outer and inner frames are composed of multiple bodies, they must be linked together using contact definitions. A bonded contact, formulated using the augmented Lagrange algorithm, is used to define the body connection between the inner and outer frames. In addition, the frames interact with each other and with the ground using frictionless contact, meaning that no penetration is allowed and no friction forces are calculated.

3.2.1. Face-drop scenario

Figure 6 illustrates the displacement of the inner frame along the Y-axis as a function of time. No rotation is observed; both frames translate purely along the vertical Y-axis. Amplitude decreases over time due to energy dissipation. After the drop, the inner frame stabilizes at a spring deflection of 0.005 m, indicating that it has reached a state of static equilibrium.

Accelerations were plotted for four characteristic nodes near the cargo mass point (see Fig. 7), as the accelerations in this area indicate whether the cargo is overloaded due to impact loads.

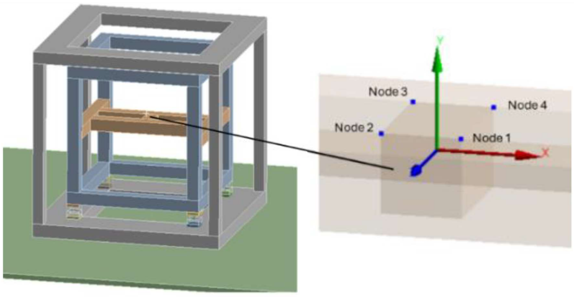

Fig. 7. The identification of nodes for plotted acceleration results.

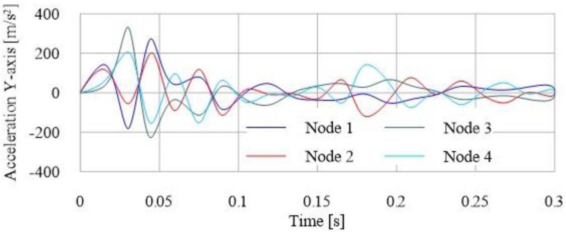

Fig. 8. Dynamic acceleration profiles of characteristic nodes for face drop.

The acceleration graph (Fig. 8) depicts the impact at times from 0.03 to 0.05 s and shows the dynamic response where oscillatory motion is attenuated due to energy dissipation. The decreasing amplitude across all nodes indicates that the shock isolation is modeled correctly, dissipating kinetic energy toward equilibrium. Displacement and acceleration plots indicate that isolators maintain the interface gap and do not generate additional shock waves in the inner frame during the analysis period.

3.2.2. Corner-drop scenario

During the corner drop, the container's outer and inner frames experience different displacements than for the face drop.

Figure 9 expresses inner frame displacement. As the rotation is noticeable, the plot reports maximum total displacement rather than the Y-axis displacement used in the face-drop scenario. The displacement exhibits dynamic behavior, which is typical of transient loading. To capture rotational effects, 5 points of interest were analyzed. The trajectories provided in the chart show the inner frame displacement at these points. Initially, the upper vertex of the bottom surface is at a height of 0.15 m. The plotted displacement indicates that the container is lying horizontally at the end of the simulation time, which was increased from 0.3 to 0.35 s to capture additional data.

The modeled shock isolation system is capable of stabilizing the inner frame even in an under-corner-drop scenario. A close examination of the system confirms that the shock isolation mounting bars maintain a gap at impact, preventing engagement with the outer frame; hence, no additional shock is transmitted to the cargo.

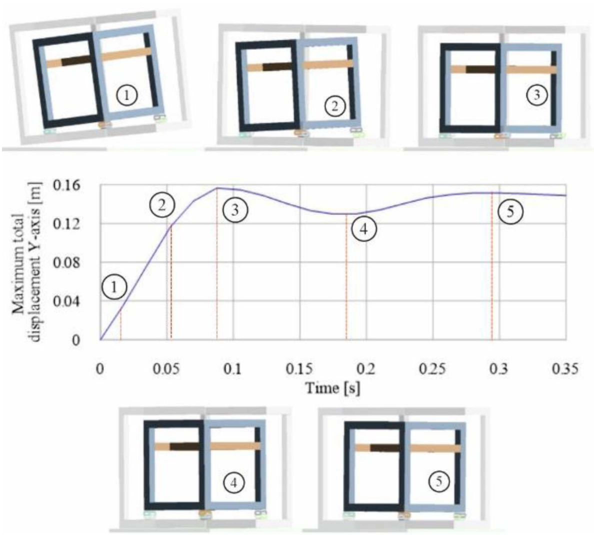

Fig. 9. Inner frame displacement under the corner-drop conditions.

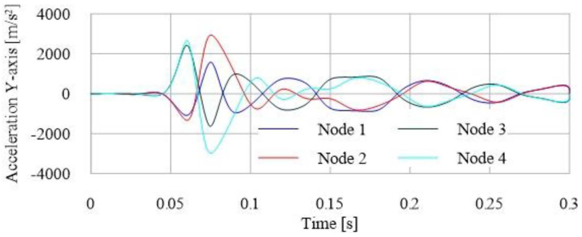

Fig. 10. Dynamic acceleration profiles of characteristic nodes for corner drop.

The acceleration plotted in Fig. 10 represents the four characteristic nodes of the system, which are the same as those for face drop (Fig. 7).

The acceleration profiles highlight that nodes 4 and 2 experience the highest peak accelerations. Two characteristic peaks indicate two impacts — first, when the container hits the ground at ~ 0.06 s, and the second when the diagonal corner contacts at 0.09 s. The second impact implies a rotational effect, which can be destructive for structural integrity. Despite damping, peak accelerations indicate a significant load is being transmitted to the cargo.

Additionally, the stress distribution for the inner frame at the point of ground contact is shown in Fig. 11. The maximum stress value is 102 MPa, and the inner frame can withstand the applied corner-drop impact loads, as the critical stress limit (235 MPa) is not exceeded. The peak stress value of the inner frame is near the mass point representing the transported cargo. This indicates that areas near the cargo fixing point can be susceptible to strength failure; therefore, for the real container design, special care should be taken to ensure sufficient endurance in this location.

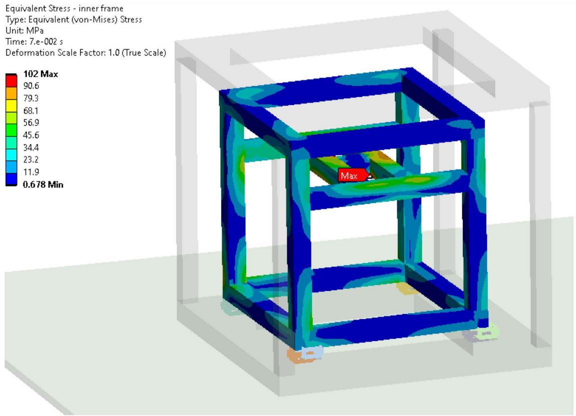

Fig. 11. Maximum equivalent von Mises stress distribution on the inner frame at the moment of corner impact.

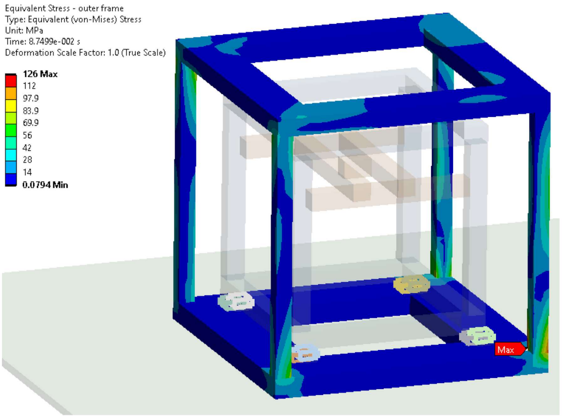

Fig. 12. Maximum equivalent von Mises stress distribution on the outer frame at the moment of corner impact.

Regarding the outer frame, the maximum von Mises stress value of 126 MPa (Fig. 12) is reached in 0.09 s, indicating a second impact after frame rotation around the collision point. The peak stress plotted for the outer frame is only 24 MPa higher than that for the inner frame. Considering the highest von Mises stress registered, there is no risk of structural plastic deformation, as the material's yield strength is ≈ 100 MPa higher than the peak stress.

4. Conclusions

The article presents a simulation of dynamic phenomena in containers for transporting sensitive cargo, which were dropped from a specified height in accordance with the data presented in the standards. The most essential element of the objects was the vibration isolation system of the internal frame, which carried the cargo. The research

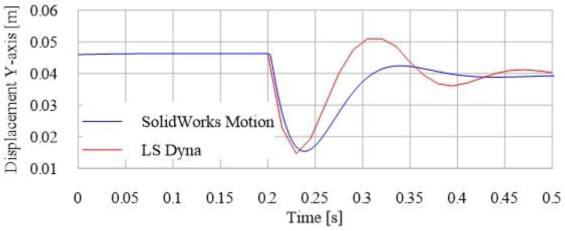

Fig. 13. Inner frame displacement under face-drop conditions.

was conducted using SolidWorks Motion and Ansys LS-Dyna programs. Based on the researcher's work, the following conclusions can be drawn:

(i) The SolidWorks Motion program is not suitable for advanced dynamic analyses as it treats structural elements as rigid elements during motion analysis, preventing accurate modeling of deformable behavior within the vibration isolation system. This approach forced the use of an equivalent system of linear springs and dampers, which were only responsible for the deflection of the spring and did not account for the transverse elasticity of the isolator. In the analyzed face-drop case, the resultant displacements of the internal frame are very similar to those determined in the LS-Dyna program (Fig. 13).

(ii) In case stresses during the drop test need to be determined, the SolidWorks Motion program performs this task by generating boundary conditions in subsequent steps and performing a classical static analysis. The user only controls what material the element is made of and the mesh density. Therefore, the results obtained during such an analysis are not entirely reliable.

(iii) Developing a model and conducting tests in LS-Dyna is much more time-consuming than in the case of SolidWorks Motion, but the scope and quality of the obtained results are much greater. In particular, during the analysis, it is possible to specifically define which elements the solver should treat as deformable and which as rigid.

(iv) The structure of the results obtained from the LS-Dyna program, as presented in the paper, provides a comprehensive understanding of the system in the two considered load cases, i.e., surface collapse and corner collapse. Key findings include detailed information on displacement patterns, their corresponding motion trajectories, and acceleration profiles. These are the primary indicators for evaluating the performance of the structure under impact conditions, which can also facilitate the optimization of the proposed solution.

In summary, it can be stated that SolidWorks Motion can be responsibly used only for kinematic analyses, while Ansys LS-Dyna can be used for dynamic analyses. Based on the obtained results, it can be tentatively assumed that the numerical simulation results can serve as a reliable source of data, potentially eliminating the need for time-consuming and expensive physical tests of such structures. However, for this purpose, experimental verification must be carried out, which will be the next stage of the authors' work.

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