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Article

On the Issue of Shipping Container Side and Rear Damage During Port Handling Operations

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Abstract: The damage to shipping containers during port handling operations continues to pose a significant challenge that adversely affects operational efficiency, equipment integrity, and supply chain accountability. This study utilises real-world measurement data gathered through accelerometers to examine the occurrence and dynamics of physical impacts, particularly side and rear collisions, during the handling of containers at Klaipėda City Port. The research prioritises two critical scenarios: side impacts occurring during stacking operations with reach stackers and rear impacts during trailer loading procedures. Impact events were meticulously recorded and analyzed to ascertain the magnitudes of acceleration across multiple axes. This reveals that side impacts produce significantly greater forces, particularly in the lateral direction, than rear impacts. The study employs sensor-based monitoring, advanced data visualization techniques, and structured scenario analysis to delineate the variability and intensity of mechanical interactions during these operations. The findings emphasise the structural stress that containers experience and underscore the importance of embedded monitoring technologies for real-time event detection and damage prevention. The results contribute to the expanding body of knowledge that supports the digital transformation of container terminals and furnish actionable insights for enhancing handling protocols, informing insurance assessments, and improving safety measures within both automated and conventional port environments.

Keywords: Container handling operations; Impact detection; Port terminal monitoring; Smart sensor systems

1. Introduction

Shipping containers are the structural cornerstone of modern global trade [1–3], enabling standardised, modular transportation of goods across continents with unmatched efficiency. With millions of twenty-foot equivalent units (TEUs) processed annually, container ports have become high-throughput environments where speed, coordination, and mechanical precision are vital for maintaining global supply chains [4,5]. Yet, within this highly optimized system, container damage during handling operations remains a persistent and costly issue [6,7]. From operational delays and insurance disputes to equipment failure and safety risks, the consequences of mishandled containers ripple through the entire logistics network [8,9].

Container damage in port environments typically occurs during loading, unloading, and transshipment procedures. These operations often involve heavy machinery such as quay cranes, gantry cranes, reach stackers, and automated guided vehicles (AGVs), all interacting with containers dynamically and sometimes unpredictably [10,11]. Containers are lifted, swung, aligned, and lowered within confined spaces, often under tight time constraints and in variable weather conditions. While containers are designed to withstand harsh conditions, their structural integrity is

often compromised by high-impact forces, repeated stress cycles, and unintentional collisions with port infrastructure or other containers. Key points of vulnerability include the corner castings, sidewalls, and bottom rails, which may suffer crushing, denting, or bending due to poor alignment during crane engagement, excessive swing during lifting, or uncontrolled descent during placement [12]. This damage is not merely cosmetic; it can compromise the container's ability to seal properly, reduce its load-bearing capacity, or interfere with stacking mechanisms on board ships and within container yards (see Figure 1).



Figure 1. Examples of container damage resulting from bad handling operations.

Furthermore, when damaged containers go undetected, they pose risks to cargo security, terminal personnel, the overall structural integrity of the port, and other valuable equipment. Given the scale and pace of containerized logistics [13], relying solely on visual inspection and manual reporting to detect damage is increasingly inadequate. Human-based assessments are limited by visibility, access, time, and subjective judgment. As a result, many damage events go unnoticed until significant deterioration or secondary complications arise [14]. This delay in detection often leads to more extensive repair costs, shipment delays, and disputes between shippers, terminal operators, and insurers. Moreover, visual inspections fail to provide forensic insight into when, where, or how the damage occurred, as data is essential for accountability, process optimization, and preventive measures.

This is where smart event monitoring emerges as a crucial component of modern container handling [15–18]. In this context, event monitoring refers to the real-time or near-real-time tracking of physical interactions and impact events involving containers during handling operations. Using sensors, data acquisition systems, and signal processing algorithms enables detecting, classifying, and logging events such as collisions, hard landings, excessive swings, and other anomalies during crane or AGV operations. The availability of this data allows operators to gain a deeper understanding of operational dynamics, identify risky procedures [19–23], and take proactive measures to mitigate future damage. Event monitoring systems generally depend on accelerometers, gyroscopes, vibration sensors, or other non-invasive measurement tools that can be integrated into existing port equipment (see Figure 2).

These systems collect high-resolution motion and impact data, automatically classifying events based on severity, direction, frequency, and duration. Advanced systems can even correlate these events with specific handling procedures, container IDs, operator actions, or crane paths, creating a digital audit trail of container movements within the terminal. The significance of such systems extends beyond operational efficiency [24,25]. From a safety perspective [26], undetected container damage can lead to lifting, stacking, or transportation accidents. A weakened corner fitting or misaligned frame may cause load instability or equipment malfunction, putting workers and cargo at risk [27,28]. From a financial standpoint, demonstrating when and where damage occurred can aid in resolving insurance disputes, enforcing liability clauses, and reducing the incidence of false claims.

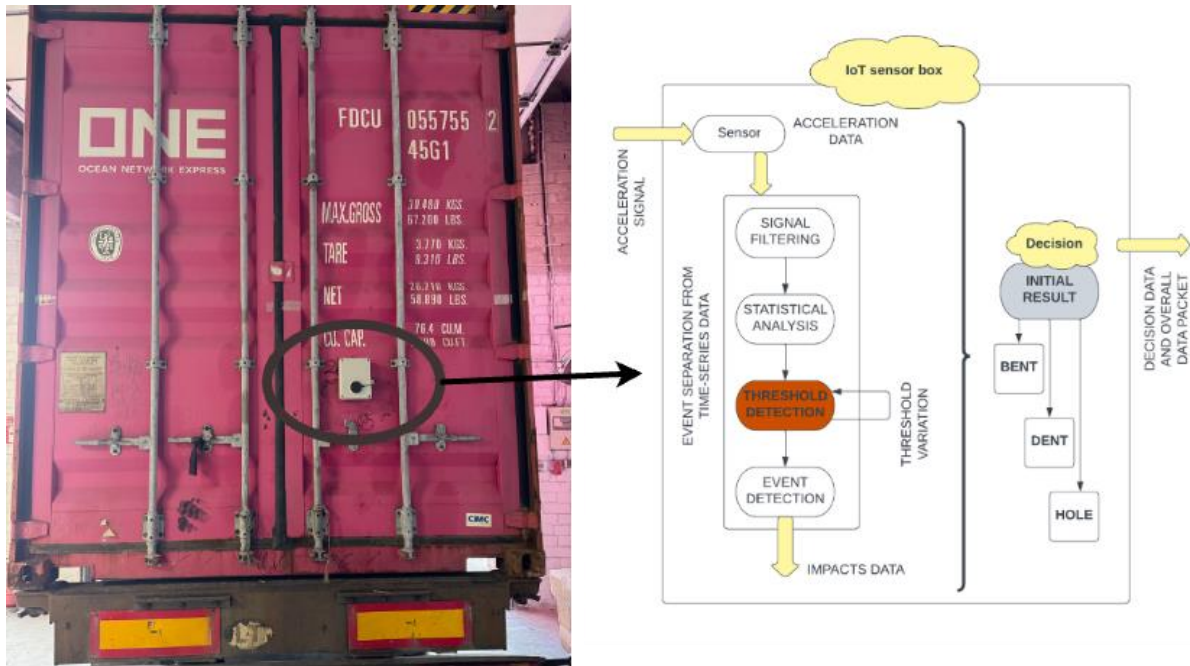


Figure 2. Examples of container damage detection systems [29] that the authors used. (The scheme on the right illustrates the principle of critical incident detection when a device is mounted on the container's door, acquiring acceleration data in real time and checking whether it has reached the predetermined threshold value.).

In a data-driven terminal environment, this level of transparency also fosters enhanced operational awareness, facilitates more informed decision-making, and enables the implementation of predictive maintenance practices. By continuously collecting and analyzing data from handling equipment and container movements, terminal operators can identify emerging patterns, anticipate equipment failures, and schedule maintenance activities based on real-time usage and stress indicators, rather than relying on static time intervals. This transition from reactive to proactive maintenance significantly reduces unexpected downtime, prolongs the service life of critical assets, and enhances overall terminal efficiency. Moreover, such transparency bolsters continuous improvement strategies by systematically identifying inefficiencies, recurring operational bottlenecks, and sources of damage, which can be addressed through process re-engineering or targeted training programs. Event monitoring also aligns closely with the broader objectives of digitalization and automation currently reshaping the maritime and logistics sectors. As ports transform into intelligent infrastructure ecosystems, integrating event monitoring data with terminal operating systems (TOS), enterprise resource planning (ERP) tools, and digital twin platforms lays a crucial foundation for more adaptive and intelligent control systems. This integration provides real-time situational awareness and promotes data fusion across various operational layers, encompassing crane dynamics, container flow, safety management, and asset tracking. Event monitoring supports the creation of predictive algorithms that evaluate risk levels and anticipate potential disruptions before they occur. For example, identifying unusual impact frequencies or force levels among similar equipment may indicate systemic alignment problems or mechanical wear, leading to necessary recalibration of crane operations, adjustment of spreader arms, or modifications of control sequences. Likewise, recurring error patterns tied to specific shifts or personnel may reveal the necessity for retraining, updating procedures, or altering user interfaces.

In fully or semi-automated terminals, this data proves to be particularly significant in enhancing the motion profiles and control logic of robotic systems, including automated stacking cranes (ASCs), automated guided vehicles (AGVs), and quay cranes equipped with intelligent spreaders. By integrating feedback from event monitoring systems, these automated components can adjust movement trajectories, acceleration rates, and engagement timings to mitigate collision risks and

mechanical stress, thereby enhancing operational precision and decreasing the probability of container damage. Ultimately, the amalgamation of event-based data analytics and automation promotes a safer, more resilient, and highly optimized port environment, enabling terminals to address the escalating demands of global trade with agility and intelligence. Importantly, the benefits of event monitoring are not confined to high-end, fully automated ports [30–32]. Even in traditional or semi-automated terminals, retrofitting handling equipment with affordable sensors and utilizing cloud-based analysis tools can significantly improve visibility and responsiveness. Modular systems can be deployed selectively at high-risk handling points, during pilot phases, or for especially valuable cargo, facilitating a scalable adoption that aligns with the terminal’s operational and budgetary constraints. However, challenges remain in standardizing the data formats, threshold criteria, and interpretation frameworks associated with event monitoring. Questions about sensor calibration, false positives, data overload, and real-time processing must be addressed to ensure operational usability. Moreover, privacy, cybersecurity, and data governance must be carefully managed, especially as ports begin to integrate such systems into broader logistics platforms and supply chain networks. In summary, although the issue of shipping container damage at ports has long been recognised (making it the primary goal of our research group, see Figure 3, the tools available to detect, prevent, and learn from these incidents have fallen behind in operational complexity.

Event monitoring represents a crucial advancement in this regard, providing detailed visibility into handling dynamics and a pathway toward more resilient, safe, and accountable terminal operations [33–35]. As global trade continues to grow [36] and terminals strive to balance throughput with safety, the widespread adoption of real-time impact detection and event logging [37–40] will become advantageous and essential.

This article further examines the problem of container side impacts that occur during stacking operations in port environments. Specifically, it investigates the mechanical interactions and misalignments that arise when containers are positioned within ship hulls or stacked vertically in yards, where precision and synchronisation between crane systems and container guides are critical. These side impacts, often resulting from lateral sway, misaligned vertical cell guides, or improper spreader positioning, represent some of the most underreported yet structurally significant forms of container damage.



Figure 3. Research performed at Klaipėda City Port Container Terminal - Limited Liability Stevedoring Company “Klaipėdos Smeltė” (fully owned by Terminal Investment Limited (TIL), a branch of MSC Group).

By analyzing the causes, frequency, and consequences of these impacts, the study aims to provide a deeper understanding of the operational dynamics that contribute to such events and to explore technological solutions—such as sensor-based monitoring and data-driven detection algorithms—that can mitigate their occurrence and enhance the overall safety and efficiency of container handling systems.

2. Analysis of Damage Causes and On-Shore Impact Scenarios

2.1. Background Statistics

Analysis of container damage in global port operations highlights critical trends that underscore the importance of enhanced monitoring and detection systems. Improper packing and inadequate container cargo securing are the primary causes of damage, accounting for approximately 65% of all reported incidents. This includes issues such as poor load distribution, insufficient bracing, and failure to follow standard packing procedures, which can shift cargo, cause crushing, or lead to collapse during handling and transit. Additionally, physical damage arising from container handling activities, such as impacts from cranes, yard vehicles, and other machinery, contributes to around 25% of the damages recorded. These incidents frequently occur during lifting, aligning, or lowering operations and are exacerbated by environmental factors, human error, and constraints due to time pressures.

Moreover, thermal damage to temperature-sensitive cargo, especially in refrigerated (reefer) containers, accounts for roughly 14% of damage incidents. Such issues generally result from equipment failures or the inability to maintain necessary temperature ranges while the cargo is in terminals or transit phases. Beyond these causes, theft and shortage-related incidents collectively contribute to a significant portion of container damage-related claims, with approximately 9% attributed to cargo theft and a further 8% to discrepancies in inventory upon arrival, often due to miscounts, pilferage, or administrative errors during port handling procedures. Container losses at sea, while often associated with vessel transit, also reflect vulnerabilities introduced during port stacking and loading. Between 2008 and 2019, the average number of containers lost annually at sea was approximately 1,382 units, with a substantial proportion—nearly 57%—directly linked to adverse weather conditions and improper stacking protocols. These figures illustrate the need for more robust securing methods, weather-responsive loading plans, and real-time monitoring of shipboard stability during container transfer operations.

Incidents occurring within port boundaries illustrate the intricate risks associated with terminal operations. In 2022, roughly 2,400 maritime incidents were documented at ports and terminals worldwide, with nearly half occurring during berthing, loading, and unloading activities. Over 800 of these incidents were linked to vessels docked at berths or manoeuvring in harbour areas, underscoring the frequency of accidents in high-density operations. Supporting this, major terminal operators like APM Terminals have reported over 1,200 container handling-related incidents in one operational year, emphasising the issue's magnitude, even in high-tech environments. Furthermore, the situation is exacerbated by significant underreporting. Minor impacts and surface deformations, which may not be visibly apparent or initially considered critical, are frequently omitted from official incident records. Nonetheless, such damage is known to diminish container value by about 2–5%, which impacts asset utilisation and heightens downstream logistical risks. These statistics (summarised in Table 1) strongly support implementing continuous, data-driven monitoring systems in port operations.

Table 1. Statistics of events.

Cause of Damage	Statistic	Source
Improper packing and securing	65% of cargo damage claims are due to poor packing and securing	Officially provided by the Global Trade Magazine “ https://globaltrademag.com/ ”

Physical damage during handling	25% of cargo damages are attributed to physical handling damage	Officially provided by the IFA Forwarding “ https://ifa-forwarding.net/ ”
Containers lost overboard	11% of cargo damage claims are due to containers lost at sea	Officially provided by the Container xChange “ https://www.container-xchange.com/ ”
Temperature-related damages	14% of cargo damages are due to incorrect temperature	Officially provided by the IFA Forwarding “ https://ifa-forwarding.net/ ”
Theft-related damages	9% of cargo damages are due to theft	Officially provided by the IFA Forwarding “ https://ifa-forwarding.net/ ”
Shortage-related damages	8% of cargo damages are due to shortages	Officially provided by the IFA Forwarding “ https://ifa-forwarding.net/ ”
Maritime incidents in ports and terminals	2,400 incidents recorded in 2022; ~50% occurred within port boundaries	Officially provided by the Port Technology “ https://www.porttechnology.org/ ”
Incidents at berth or harbor	813 incidents occurred while docked in ports and harbors in 2022	Officially provided by the Port Technology “ https://www.porttechnology.org/ ”
APM Terminals incidents	Over 1,200 incidents reported globally in 2019	Officially provided by the BoxOnWheel “ https://boxonwheel.com/ ”
Unreported container damages	Minor damages can reduce container value by 2–5%; many incidents go unreported	Officially provided by the Identec Solutions “ https://www.identecsolutions.com/ ”
Average annual containers lost at sea	Approximately 1,382 containers lost annually between 2008 and 2019	Officially provided by the Standard Club “ https://www.standard-club.com/ ”
Adverse weather as cause of container loss	57.14% of container loss incidents attributed to adverse weather conditions	Yi et al., [41]

The significant impact-related damage rate, environmental unpredictability, and the shortcomings of manual inspections call for a shift towards smart detection, threshold-based alerts, and detailed logging of container handling activities. By adopting these strategies, the port logistics industry can effectively decrease the frequency and severity of container damage and its hidden costs.

2.2. Use Cases with Stacking Operations On-Shore

A use case study examined the dynamics occurring during container stacking operations at the terminal when containers placed side by side collide. In the first scenario, the containers were transported using a reach stacker-type handler (see Figure 4). Vibrations resulting from these impacts were measured using an accelerometer (model: Slamstick). The measurements took place on 2025-02-26 within the Klaipeda city port area.

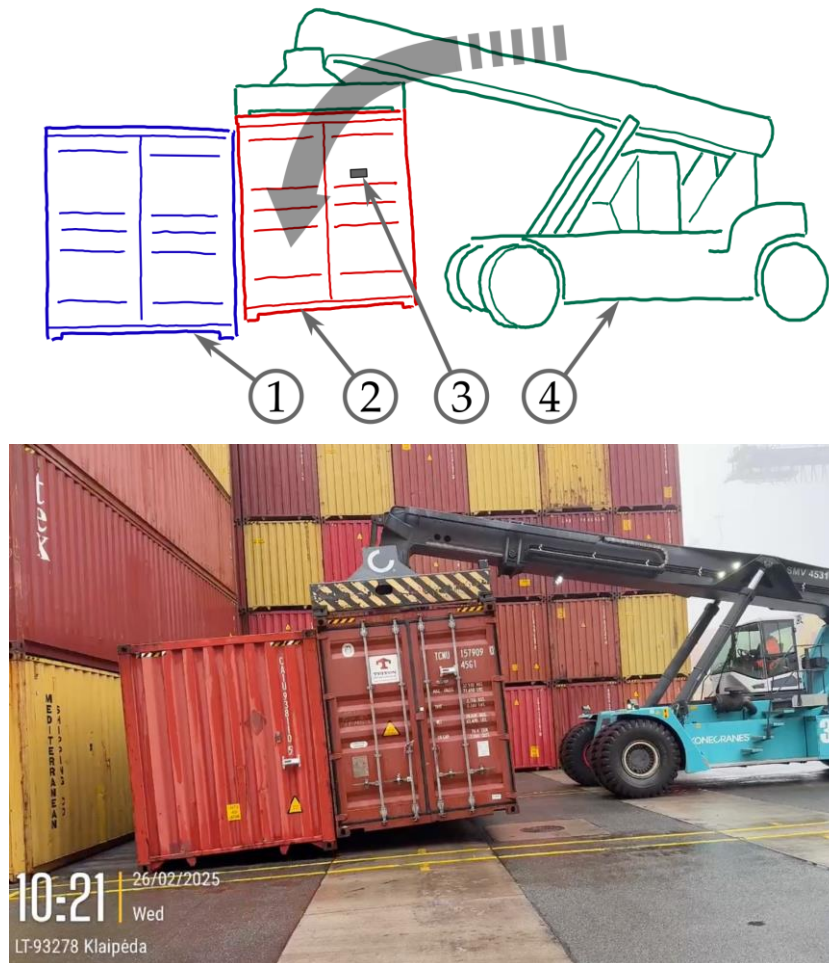


Figure 4. Schematic illustration of side impact during container stacking using a reach stacker (here: 1 – illustrates the stacked container; 2 – illustrates the container being handled; 3 – the smart container device “Slamstick”; 4 – being the reach stacker-type handler).

A second observed scenario involves rear impacts, which occur when containers make contact at their rear walls (see Figure 5). These collisions typically take place during loading operations onto truck trailer platforms within the terminal, and in most cases during other logistics operations on land.

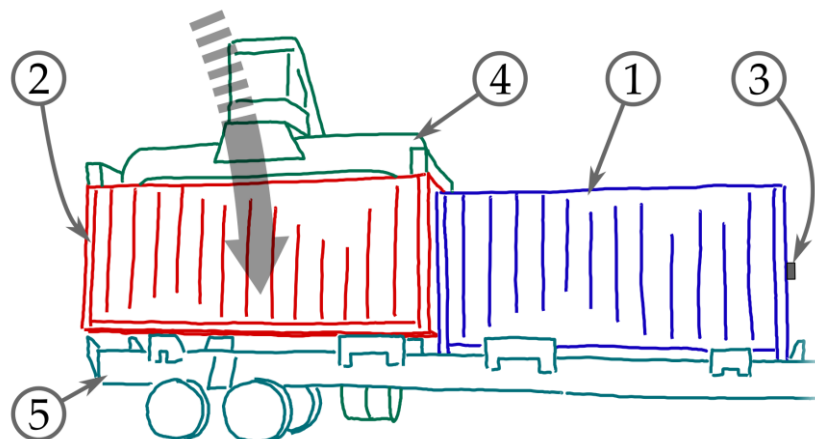




Figure 5. Rear impact between containers during loading onto a truck trailer platform.

These real-world observations emphasise the frequency and variability of impact events during routine container handling operations, reinforcing the need for continuous monitoring and data-driven analysis to enhance safety and minimise structural damage, particularly within terminal environments. This approach empowers engineers and port operators to make informed, evidence-based decisions in contexts such as customs inspections, insurance claims, and compliance monitoring.

3. Results

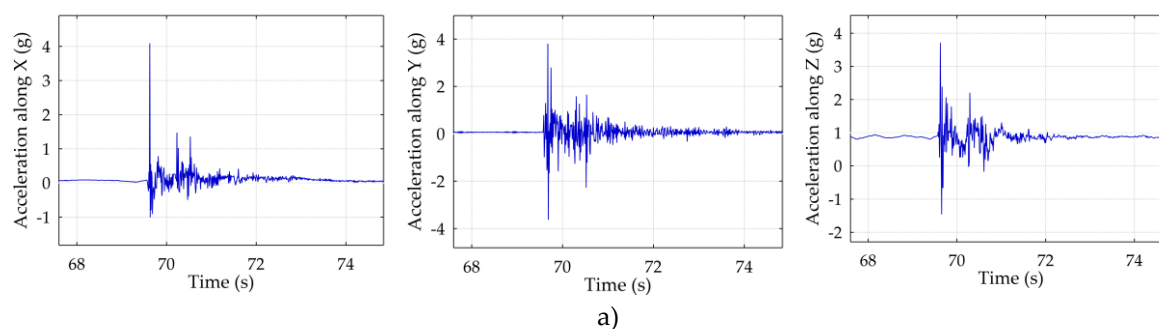
This section presents the findings of a use case study conducted at the Klaipėda City Port container terminal, operated by Klaipėdos Smeltė, on February 26, 2025. The study aimed to capture real-world impact dynamics during container handling operations. Measurements focused on two typical scenarios using a reach stacker container handler:

- (1) side impacts during stacking in container yards.
- (2) rear impacts during loading onto truck trailers.

3.1. Side Impact Measurements

Side impacts were observed as containers were stacked side by side, causing collisions along their longitudinal walls. An accelerometer (Slamstick model) was mounted on the moving container to record impact-induced vibrations. Four distinct impact events were recorded:

- 10:21:34 (see figure 6a) – Peak acceleration: X = 4.1 g, Y = 3.8 g, Z = 3.9 g.
- 10:23:00 (see Figure 6b) – Peak acceleration: X = 7.2 g, Y = 3.2 g, Z = 4.2 g.
- 10:24:22 (see Figure 6c) – Peak acceleration: X = 2.3 g, Y = 5.1 g, Z = 2.7 g.
- 10:26:26 (see Figure 6d) – Peak acceleration: X = 3.2 g, Y = 3.8 g, Z = 2.3 g.



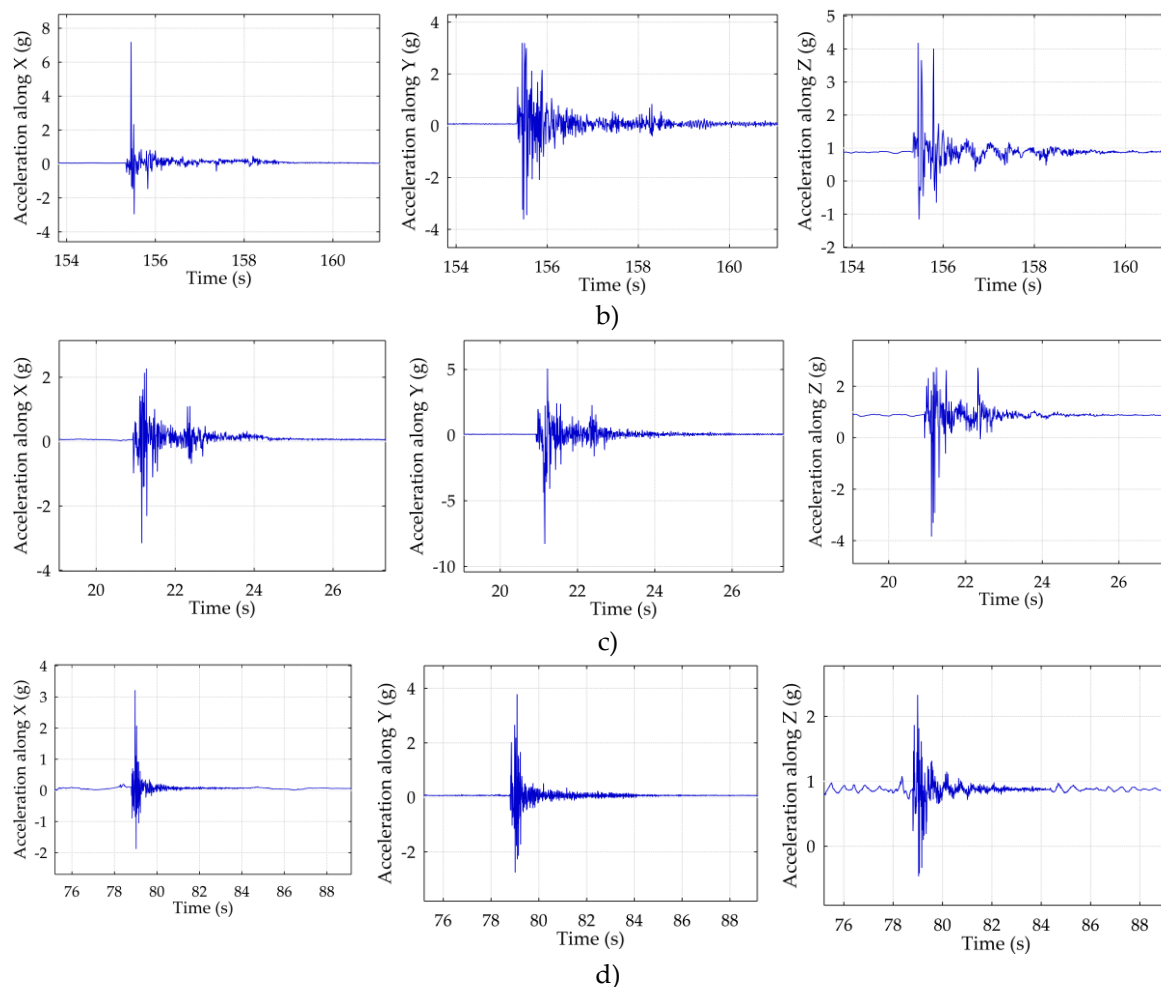
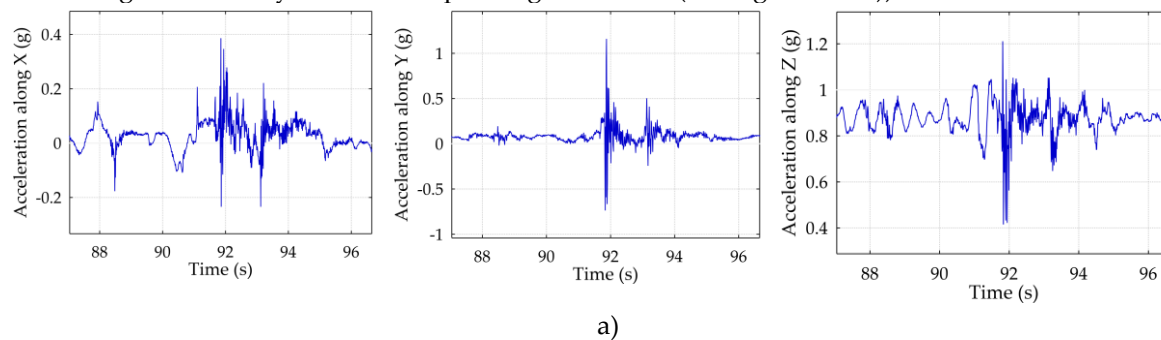


Figure 6. Side impact measurements (a-d).

These results indicate that lateral collisions during stacking can induce substantial multi-axial accelerations, with peak values reaching up to 7.2 g.

3.2. Rear Impact Measurements

Rear impacts were identified when containers contacted each other or infrastructure at their rear walls—most frequently during loading onto truck trailers. Accelerometers were attached to either the moving or stationary container depending on the test (see Figure 7a - e)).



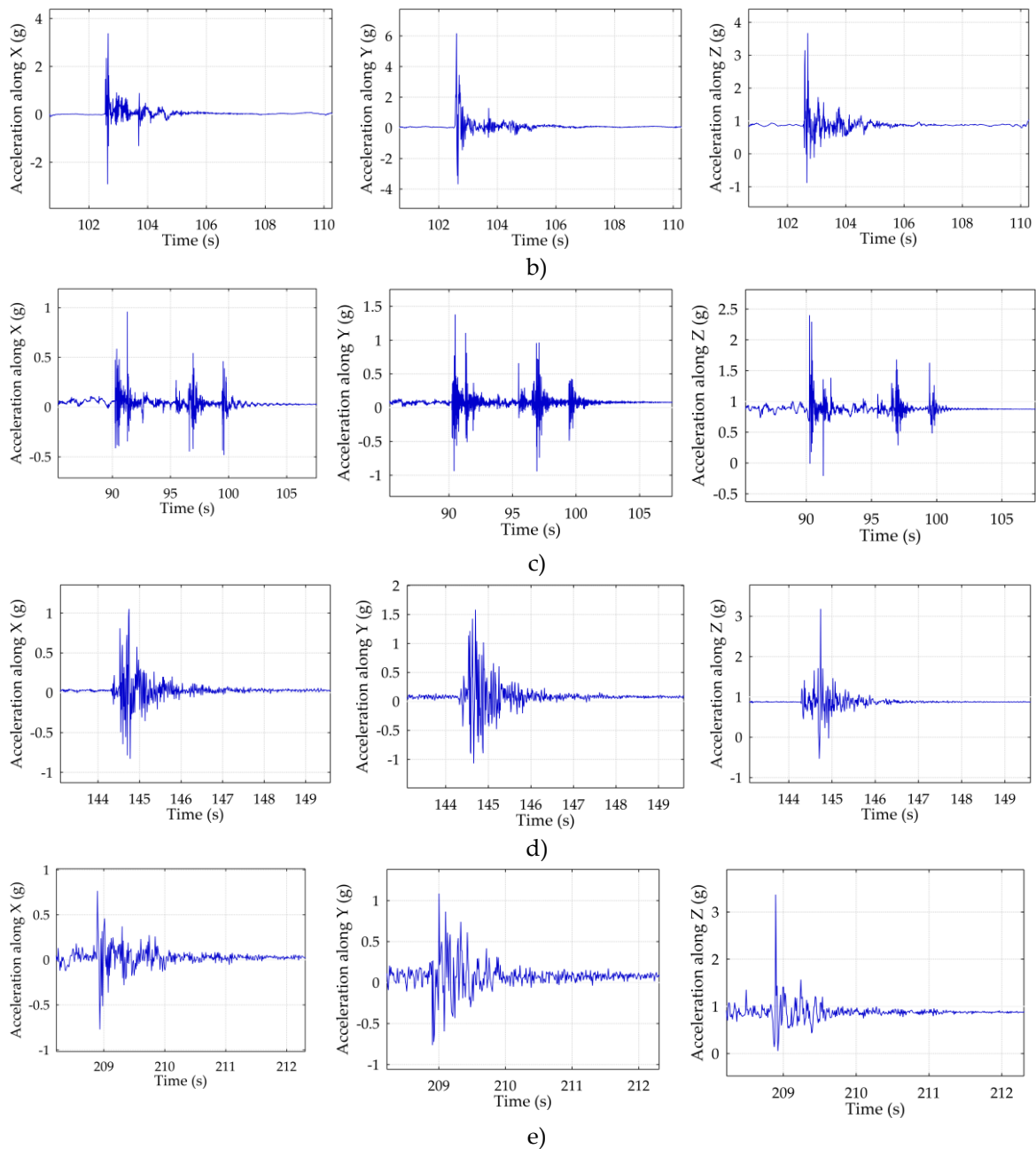


Figure 7. Rear impacts measurements (a-e).

Five impact events were analyzed:

- 10:39:56 (mild impact) – X = 0.4 g, Y = 1.2 g, Z = 1.2 g.
- 10:40:06 (aggressive impact) – X = 3.4 g, Y = 6.2 g, Z = 3.7 g.
- 10:43:17 (mild impact) – X = 1.0 g, Y = 1.4 g, Z = 2.4 g.
- 10:44:06 (aggressive impact) – X = 1.1 g, Y = 1.6 g, Z = 3.2 g.
- 10:45:10 (mild impact) – X = 0.8 g, Y = 1.1 g, Z = 3.4 g.

Compared to side impacts, rear impacts generally produced lower acceleration values, though certain aggressive collisions exceeded 6 g on the Y-axis.

3.3. Interpretation

The recorded data clearly demonstrates the range of forces containers are subjected to during typical handling operations. Side impacts yielded the highest accelerations, particularly on the horizontal axes, while rear impacts showed notable but generally lower forces see Figure 8. These insights highlight the structural stress containers endure in real-world conditions and reinforce the value of embedded sensor technologies for event detection and operational diagnostics. Continuing the presented results, the radar chart compares the average acceleration values recorded across the X, Y, and Z axes for both side and rear impact scenarios. Side impacts exhibited consistently higher average accelerations, particularly along the X-axis, indicative of strong lateral forces generated during stacking operations.

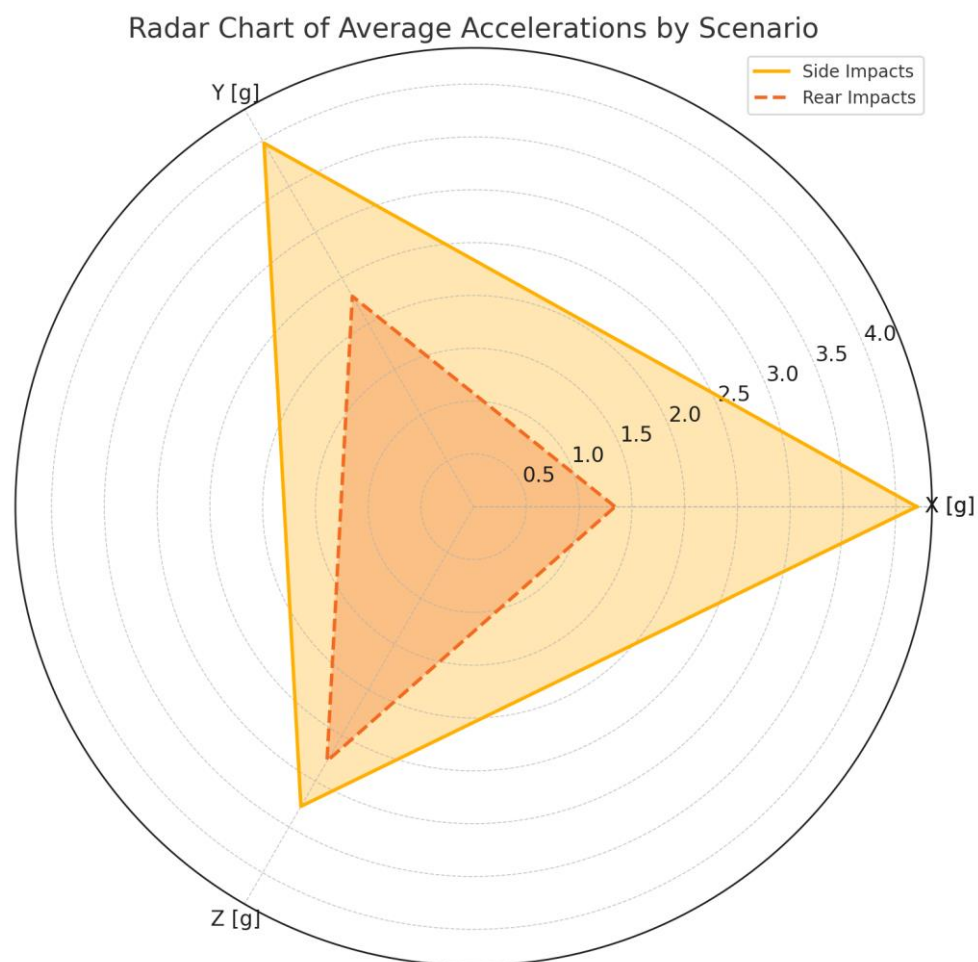


Figure 8. Radar Chart of Average Accelerations by Scenario.

Rear impacts, in contrast, displayed a more compact profile, with generally lower acceleration values, except for a moderate increase along the Y-axis—likely due to vertical motion during container placement onto truck trailers. This contrast in impact profiles illustrates the differing mechanical stresses containers are subjected to depending on the specific handling scenario, further emphasising the importance of scenario-aware monitoring and mitigation strategies within terminal operations.

4. Discussion

The findings of this study align with previous literature emphasising the vulnerability of containers during mechanical handling, particularly under high-throughput conditions common in modern terminals. While prior work has broadly addressed damage detection systems and risk mitigation frameworks, this research offers an empirical contribution by quantifying real-world

impact forces through embedded sensor technology. The measured accelerations in side impact events exceeded those recorded in rear impacts by a substantial margin, particularly along the X-axis. This confirms the operational hypothesis that lateral misalignments during stacking are among the most damaging handling events. These insights correlate with incident data suggesting underreporting such impacts due to their often non-visible external consequences. The radar visualisations further reinforce the multidirectional nature of container stress and illustrate the potential for pattern recognition and predictive alerting within smart terminal environments. Moreover, the distinction between aggressive and mild impacts, documented in stacking and trailer loading scenarios, demonstrates embedded sensors' sensitivity and capability to classify severity levels, a key requirement for scalable event monitoring systems. While this study focused on specific handling cases using a reach stacker, the findings suggest a broader applicability for similar sensor-driven frameworks across different terminal configurations and equipment types. Future research may extend these insights through long-term deployment, multi-sensor fusion, and integration with terminal operating systems for automated response.

5. Conclusions

This study presented a use case analysis of container damage mechanisms during port handling operations, focusing on side and rear impacts as recorded by onboard accelerometer devices. The results clearly show that side impacts during stacking generate higher and more variable acceleration profiles than rear impacts during trailer loading. These differences emphasize the importance of distinguishing between handling scenarios when evaluating structural risk and designing monitoring solutions. The successful capture and classification of impact data demonstrate the feasibility of implementing smart sensor-based systems in real operational contexts. Such systems can provide actionable intelligence for operators, insurers, and terminal managers by supporting damage documentation, liability resolution, and preventive decision-making. Integrating these insights into broader digital port infrastructure can help foster safer, more efficient, and data-driven container handling practices. As container logistics continue to evolve, real-time impact detection will be essential for optimizing performance, maintaining asset value, and enhancing resilience in both automated and manually operated terminal environments.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

TEU	Twenty-foot equivalent units
AGVJ	Automated guided vehicle
TOS	Terminal operating systems
ERP	Enterprise resource planning

ASC Automated stacking cranes

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