REVIEW

Review on Design and Simulation Methods for Standard Freight Container Lashing

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ABSTRACT

Secure lashing and fixing of freight containers is a significant provision in structural integrity and in preventing loss of cargo during maritime transport. The classical model of container lashes is largely based on quasi-static assumptions as required by the international standards that are inclined to underestimate the actual dynamic forces due to ship motions, wave excitation and resonance effects. The disadvantages of these types of fixed design solutions have been proven in the recent incidents of huge container losses. This review provides a critical analysis of the analytical, numerical and experimental methods that are used in the evaluation of the standard freight container lashing systems. Particular attention is paid to finite element analysis (FEA), computational fluid dynamics (CFD) and multi-body dynamics (MBD) techniques that are applied to simulate realistic loading conditions. The recent advances in the multi-physics coupling, scaled-model experimental validation techniques, and full-scale experimental validation techniques, the new tendencies of machine-learning prediction of lashing forces, and digital twins of real-time monitoring are critically analysed. The key gaps in the study related to the dynamic load representation, regulatory constraints, and validation practices are outlined. This review is aimed at providing researchers and marine engineers with a systematic understanding of the

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existing methodologies and future trends in research on the improvement of safety and reliability of container lashing systems in real-life operation conditions.

Keywords: Freight Containers; Container Lashing Systems; Finite Element Analysis; Dynamic Loads; Regulations; Digital Twin; Machine Learning

1. Introduction

Shipping has been used for cargo transportation since ancient times, when marine trade served as the basis for both cultural and economic exchange. Early vessels, such as Indian and Egyptian merchant ships used to transport cargo across the seas. These ships had open decks or simple wooden hull where cargo was stacked manually, often tied with ropes and cushioned with naturally available materials to reduce movement. Materials such as grains, oil, and wine were typically stored in amphorae (narrow-necked pottery vessel) which were carefully arranged upright in the ship's hold, often stored in sand or straw to cushion them and prevent movement. Although lacking in standardization, these early methods laid the foundational principles for modern cargo stowage.

The primary objective of the review is to critically review the existing design, simulation, and experimental techniques for assessing freight container lashing systems. The paper will identify the weaknesses of current statical-based regulatory models, evaluate the advancement of numerical and multi-physics simulation models, and describe the new research directions that may improve the safety and reliability of container securing in the dynamic maritime loading conditions.

Before the introduction of standardized containers to the shipping industry, cargo handling was labour-intensive, time consuming and prone to damage or theft. The development of containerization transformed the world trade in the mid-20th century and changed the mode of transportation of goods between various continents. Malcolm McLean created the standard shipping container in 1956, which greatly improved the efficiency of the global supply chain and made it simple to move freight between trains, trucks, and ships.

Cargo security, especially freight containers, is the most important in maritime transport to reduce the risks of container collapses, ship instabilities, and the risk of casualties in case of unfavourable weather conditions at sea [1]. Misplaced and improper securing of cargo are the key causes of accidents at sea, which result in huge losses of money and loss of life [2]. The ever-increasing trend of containerization in international trade, which constitutes 80% of goods shipped by ship further increases the necessity of sound lashing designs and effective simulation techniques to avoid loss of containers at sea, which is estimated at about 1274 units per year in the past 10 years, without any catastrophic incidents [3]. Although regulatory authorities such as the International Maritime Organization (IMO) have put in place measures, including the verified gross mass requirement of containers, to improve safety and stability testing, there are still challenges, especially in regard to dynamic forces that are encountered in extreme weather conditions [4]. International regulations and classification society guidelines such as the IMO Code of Safe Practice for Cargo Stowage and Securing and International Organization for Standardization (ISO) standards of the relevant standards, largely based on the assumption of a static or quasi-static loading, give the design limits of container lashing systems. Even though these rules offer minimum safety standards, they do not directly address such dynamic effects as parametric roll, resonance and load amplification caused by the impact of waves. Several experiments have demonstrated that dynamic ship motions can significantly increase lashing forces to values that are significantly higher than regulatory values determined in a static analysis. This mismatch between the assumptions of regulatory design and the reality of the working conditions indicates that dynamic load modelling and verification through

simulation should be incorporated in future container lashing design requirements. Nevertheless, the cases of containers being lost at sea persist, and it is estimated that about 3000 containers have been lost overboard in 2020 alone, which points to the ongoing difficulties in ensuring the integrity of cargo under extreme conditions [5]. Poor design of container lashing has its implications, which are reflected in a number of disastrous accidents that have been reported in the past few years. The most notable example is the container ship ONE Apus that lost more than 1,800 containers in a serious storm in the Pacific Ocean in 2020. Research studies found that high dynamic loads, motion due to waves and resonance were also significant causes of failure of container securing systems. These accidents suggest that there is a need to improve dynamic analysis and validation-based lashing design methods. This necessitates a deeper investigation of the intricate interactions of ship motion, container stack behaviour, and lashing system behaviour, especially under strong environmental pressures [6]. One of the most important aspects to be taken into account is that the existing regulations of lashing equipment are mostly assessed on the premises of the static loads, which do not always reflect the dynamic nature of forces that are experienced during maritime transportation [6]. This mismatch between the operating reality that is dynamic and the regulatory evaluation that is static often leads to underestimation of the actual lashing forces, which enhances the loss of containers and structural damage [7]. The paper will give a summary of the design and simulation techniques that are being applied to the normal freight container lashing, any gaps that exist and propose future research directions to seal these dynamic gaps. In particular, a dynamic behaviour of freestanding packages, including rocking, sliding and jumping in reaction to the acceleration of a vehicle, is one of the key elements that are frequently neglected in the traditional static analysis [8]. These dynamic behaviours are what determine the real forces on lashing systems, which are usually greater than the design limitations [9]. Such negligence may cause significant losses to cargo and risk accidents [10]. To make these problems even more complicated,

the growing size and complexity of modern container vessels bring about new problems in lashing design because larger vessels are vulnerable to higher inertial forces and more pronounced resonant frequencies, which may intensify the dynamic stresses of lashing systems [6]. As an example, ultra-large containerships are increasingly using external lashing systems and lashing bridges, which, although they have higher aspect ratios, tend to be less stiff than the hull structure, which has a direct impact on the structural response and force distribution on container stacks [7]. This structural flexibility, combined with the natural dynamic excitation of the ship motions, requires sophisticated simulation methods that are able to accurately model the complicated interaction between container stack behaviour and the lashing system in the real-world operating conditions [11]. The remainder of this paper is organized in the following manner. In Section 2, an introduction to the standard freight container lashing systems, parts, and the international regulations is provided. Section 3 discusses analytical methods, numerical methods and experimental methods of the evaluation of lashing performance, including finite element analysis, computational fluid dynamics and multi-body dynamics. Section 4 discusses dynamic loading effects, validation practices, and key performance indicators. Section 5 presents the current gaps in research and new innovations and Section 6 presents the closing remarks and the future research directions.

1.1. Background of Freight Container Lashing

Container securement on ships is regulated by a number of regulations and industry practices, most of which are historically based on quasi-static methods that implicitly consider the dynamic effects by conservative safety factors [9]. Nevertheless, these conventional techniques may not be very effective in reflecting the complicated interaction of forces due to dynamic ship motions, wave impacts and coupled structural responses [12]. As an example, past design methods often studied the lashing bridge, container stack, and hull

structure separately, without considering the interaction between them and the subsequent effect on structural integrity and safety [7]. This uncoupled analysis usually results in an underestimation of lashing system stresses and structural stresses of the ship, especially in extreme sea conditions or resonant conditions [11]. Also, the optimization of container placement, known as the stowage planning, based on the terminal infrastructure, separation of dangerous goods, and stability, has a direct influence on the efficiency of lashing systems [13]. A combination of multiple dynamic processes, including the movement of the hull, the alteration of the weight and levels of the container stack, the effect of the wind and waves, and so on, could have a substantial adverse impact on the lashing system [14]. Also, the lashing bridge design is necessary in the securing of containers and is closely related to the entire ship design and the flexibility of positioning containers [11]. The lashing design must therefore not be limited to the static loads but also the dynamic forces that arise as a result of acceleration of the vessel and also the distribution of the payloads in the container stack, since they play a major role in the torque distributions and system stability in general [11]. This is a comprehensive study that considers fluid-structure interaction with the view of achieving a successful model of sloshing loads and their effects on lashing integrity, especially the nature of dynamic loads that cannot be easily predicted in fluid-filled structures [15,16].

1.2. Problem Statement

The main problem is to come up with more advanced predictive models and simulation tools that can be used to model these complex dynamic interactions, rather than just simple static assumptions. This entails developing techniques which can be employed to forecast with a high degree of certainty the extreme ship responses and the stresses on lashing systems that are connected with it, even in those conditions which lead to resonant vibrations or high fluid-structure interaction effects [17]. It is an integrated approach that is needed to prevent container losses, minimize structural losses to the vessels and ultimately enhance the

safety and efficiency of the maritime industry [11,18]. This necessitates a paradigm shift to both the advanced CFD and the FEA to simulate the coupled hydro-elastic behaviour of the ship and its cargo hence provide more realistic analysis of the lashing system behaviour.

1.3. Objectives

The primary goal of the review is to carry out a systematic evaluation and synthesis of the available literature on design and simulation methods applied to lash a typical freight container with the purpose of establishing the key advances and the current problems in the field. This will involve critical analysis of various numerical and experimental techniques and their ability, in particular, to capture the dynamic interactions between the container, lashing system and ship structure under real operating conditions. Specifically, the aim of the review is to compare the performance of different simulation techniques, such as finite element analysis, computational fluid dynamics and multi-body dynamics, in predicting lashing forces and structural responses [19]. Besides, it will assess the possibility of integrating these approaches to be integrated with advanced optimization algorithms and real-time monitoring systems to enhance the design of lashing and safety of its operation. The other objective of significant interest is to find the new trends, such as artificial intelligence and machine learning, in the optimization of lashing configurations and the prediction of potential failure modes. The cumulative assessment of this will assist in determining the discrepancy in the existing paradigms and propose the future research directions to design more resilient and predictive paradigms of container lashing systems that will address the increasing complexities of the modern maritime logistics and enhance the overall safety and integrity of vessels [20].

1.4. Scope of the Review

It will critically review the techniques of predicting forces on container stacks and lashing equipment in both stationary and dynamic states, the analytical and numerical techniques [6]. The progress in sensor technologies and data-driven models of real-time mon-

itoring and adaptive control of lashing forces will also be discussed in the review as a way to more intelligent and resilient cargo securing systems. Particular focus will be placed on the research that combines the ship motion dynamics, loads caused by waves, and container-stack interactions and assesses their effectiveness in reducing the damage to containers during port handling and transit operations [7,21]. This also involves the analysis of new lashing solutions, including external lashing, and how they affect the design and weight distribution in containers, which require strict testing of prototypes to confirm the solution [6]. Moreover, the review will explore the issues related to automation of stowage planning, especially the correct forecast of lashing forces with the help of advanced machine learning models [13]. It will also evaluate the techniques of simulating a four-tier container stack with different lashing techniques and twist lock arrangements to learn the dynamic behaviour of the stack when subjected to pre-defined rolling and pitching excitations [6]. Also, the effect of different stiffness of lashing parts on the performance of the entire system and the efficiency of the different lashing schemes (e.g., internal and external) in withstanding inertial loads will be explored in this review [6]. It will also discuss the changing rules of classification societies on container lashing systems and how these have affected design methodologies, especially with the growing design acceleration values and the appreciation of accelerations in parametric roll conditions [22]. Lastly, the implications of hull flexibility on container stack dynamics and the issues that arise in the accurate modelling of the rotational axes of ship motion in computational simulations will be taken into account [6]. It will also discuss how sub-scale model testing and full-scale experimental verification can be used to test the validity of numerical simulation of lashing systems, which will provide a gap between the theoretical predictions and actual performance [7].

2. Lashing Systems: An Overview

This part gives a background knowledge of the different lashing systems that are in use in the transport of maritime transport and their design, the opera-tion of the systems and the regulatory bodies that govern the use of the systems. It is necessary to have this background overview in order to put into perspective the further explanation of the sophisticated design and simulation methods, since the usefulness of this type of computational tools is closely linked with the deep knowledge of the physical lashing mechanisms and the limitations inherent in them [6,23]. **Figure 1** illustrated the types of lashing and the direction of load acting on the container stacks.

It will categorize lashing systems based on their structural materials, capacity to carry loads and the capacity to fit different containers and sizes of vessels, thereby establishing a standard of evaluating the validity of the simulations [7]. In addition, it will also examine the ways in which these systems have evolved as the size of ships and the cargo carried on them increased and also how the materials and designs have evolved to meet the current safety and efficiency demands. This will include the discussion of traditional rod and turnbuckle systems, semi-automatic twist locks and fully automatic lashing systems with the comparison of pros and cons of each with regards to time taken to install, safety of personnel and cargo security. It will also address the significance of twist locks in container stack security, considering the mechanical behaviour and load distribution characteristics of twist locks in a dynamic environment [24]. A detailed model of the scaled model setup has been displayed in **Figure 2**.

It will also map the regulatory environment, the key international conventions and regulations of the classification society that control the design, testing and approval of the lashing system, and will concentrate on their impacts on the operational safety and compliance. This also includes the debate on how new rules can be incorporated into the design and simulation practice such as new rules on the dynamics of container stacks and twist lock performance to make sure that there is compliance and enhanced safety standards [24]. Finally, this section will point out the importance of the appropriate lashing system selection and upkeep in lessening cargo movements and potential loss at sea, accordingly, contributing to enhanced maritime safety and environmental welfare.
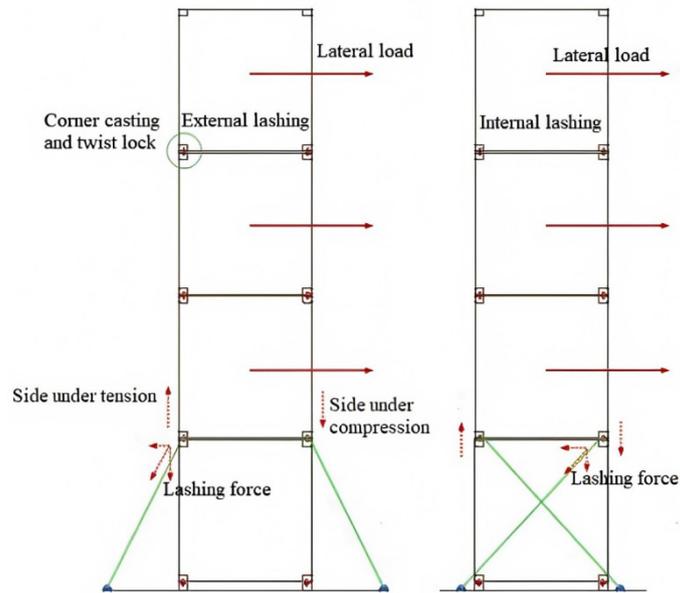
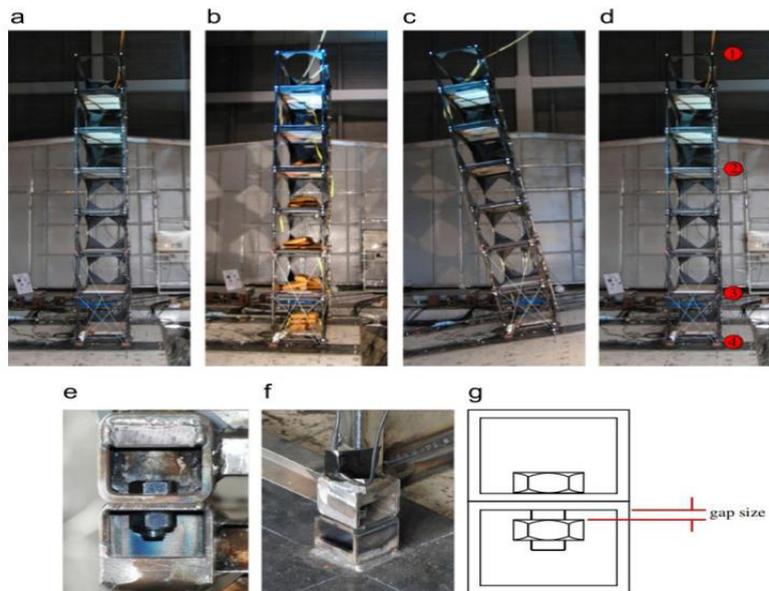**Figure 1.** External and Internal lashing systems [6].

Figure 2. Model depiction showing the non-loaded, loaded and rotated cases, with numbered points, twist-lock bolts, corner casting sockets and the initial gap between the contact surfaces [24].

2.1. Types of Lashing Equipment

Twist locks, lashing rods, and turnbuckles are the simplest components of a container lashing system, and they play a significant role in keeping the cargo at rest during transit [11]. **Figure 3** shows the components used for lashing a container and the process of lashing.

Specifically, twist locks (**Figures 4**) are needed to interlock containers in a stack, and even a small gap (e.g., 1.5 mm) can severely affect the dynamic behaviour of the entire lashing system and container stack when loaded under various conditions [6,11].

Although these clearances may appear insignificant, they may cause large relative movements between containers, which may increase the stress on lashing components and affect the overall stability of the stack [23]. This requires strict design and manufacturing tol-

erances of twist locks because even slight variations may affect the locking effectiveness and load transfer capacity of twist locks [25]. As an example, research has indicated that horizontal discontinuities in twist locks may cause 8.82% maximum difference in lashing force at the wall end and 5.76% and 7.92% difference in in- ternal and external lashing systems, respectively [6], as summarised in **Table 1**.

Such gaps can also contribute to increased twist lock tensile forces, with no-gap systems exhibiting significantly higher values compared to vertical or combined vertical and horizontal gap systems [6].
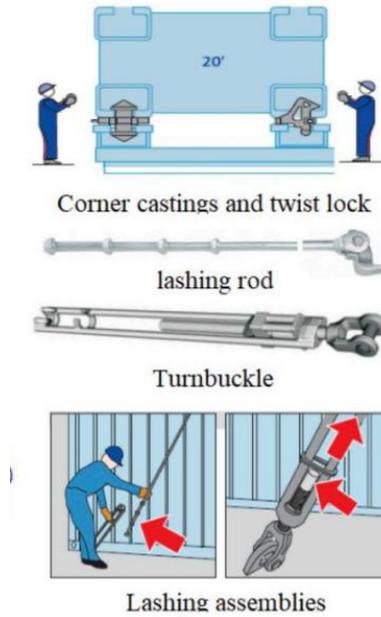
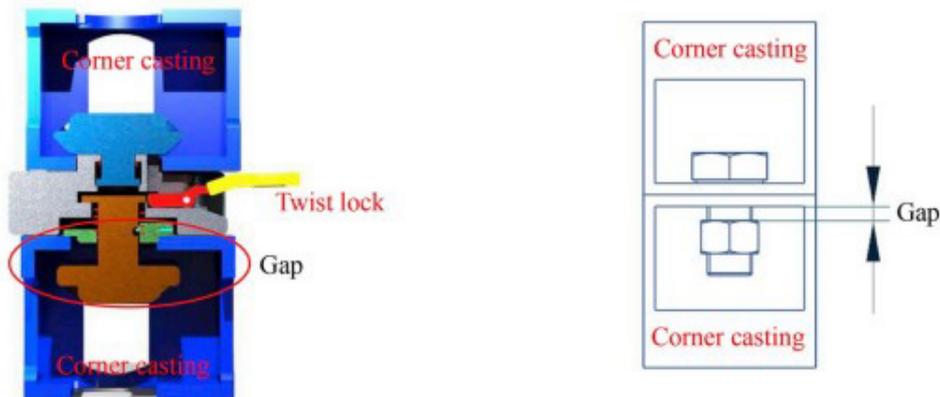**Figure 3.** Lashing components [11].

Figure 4. Twist lock details [11].

Table 1. Comparison of twist lock's tensile force [6].

Lashing Techniques	Tensile Force in Twist-Lock (N)			
	Lashing on Inside		Lashing on External Side	
	Wall	Door	Wall	Door
System without gap	86.62	42.16	26.07	0
Vertical Gap of 1.5 mm	56.31	14.56	0	0
Vertical Gap of 1.5 mm and Horizontal Gap of 0.3 mm	26.08	4.22	0	0

2.2. Materials and Manufacturing

Lashing equipment materials like high-strength steel rods, twist lock materials of special alloys are chosen due to their durability, resistance to corrosion and their capacity to resist extreme tensile and shear forces that are experienced during sea voyages. The manufacturing operations, such as forging, casting and precision machining, are carefully monitored so that these components can be of high strength and fatigue life standards and hence the integrity of the lashing system during dynamic loads. Surface finishes such as galvanization or special finishes are also commonly used to increase resistance to the severe marine environment to prevent early degradation and structural integrity throughout the life of the structure. The choice of the right materials and production methods is the most important, because the collapse of any one of the lashing elements due to material fatigue or production errors may jeopardize the stability of the whole stack of containers, which can result in the loss of cargo or the structural damage of the vessel [21]. The result of improper handling of the containers can be observed in **Figure 5**.

This highlights the importance of stringent quality control and material testing measures during the production life cycle of lashing equipment to guarantee their dependable service and durability. Moreover, the complex interaction between material characteristics and manufacturing accuracy affects the overall dynamic behavior of the stack and securing system, affecting such aspects as twist-lock and lashing force under different external excitations [9]. Lashing member stiffness, especially at the open end, and bottom twist-lock placement at the close end are important factors in improving the stability and eliminating high-frequency rolling motions exceeding design limits [9].

Figure 5. Container damage examples due to improper handling [21].

2.3. Standards and Regulations

The international maritime bodies and classification societies have developed extensive standards and regulations that regulate the design, testing and approval of container lashing systems, in order to reduce risks related to cargo shifting and loss at sea [26]. **Figure 6** shows the effect of overturning on the container stacks.

These guidelines usually specify the maximum allowable lashing forces, stability of container stacks in different sea conditions and the behaviour of individual lashing components, e.g., twist locks and rods [6]. These rules are constantly revised to accommodate the latest developments in shipbuilding technology, modifications in the design of container vessels, and the emerging knowledge of the dynamic nature of containerized cargo, especially in extreme weather conditions [27]. As an example, classification societies have recently come up with specifications to evaluate stack safety and strength checks of lashing bridge structures, which involve calculation techniques of forces on containers and lashing equipment [7]. These strict requirements are essential in making sure that securing systems are reliable and the high economic losses and safety risks that come with poor cargo securement are reduced since they contribute a significant percentage of the number of incidents of cargo damage per year [28]. **Figure 7** quantifies the operational improvements resulting by the adoption of the CTU code.
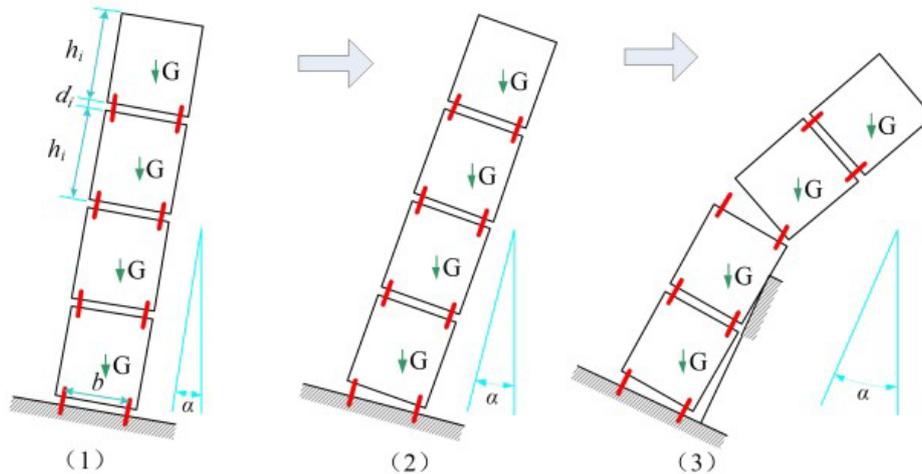
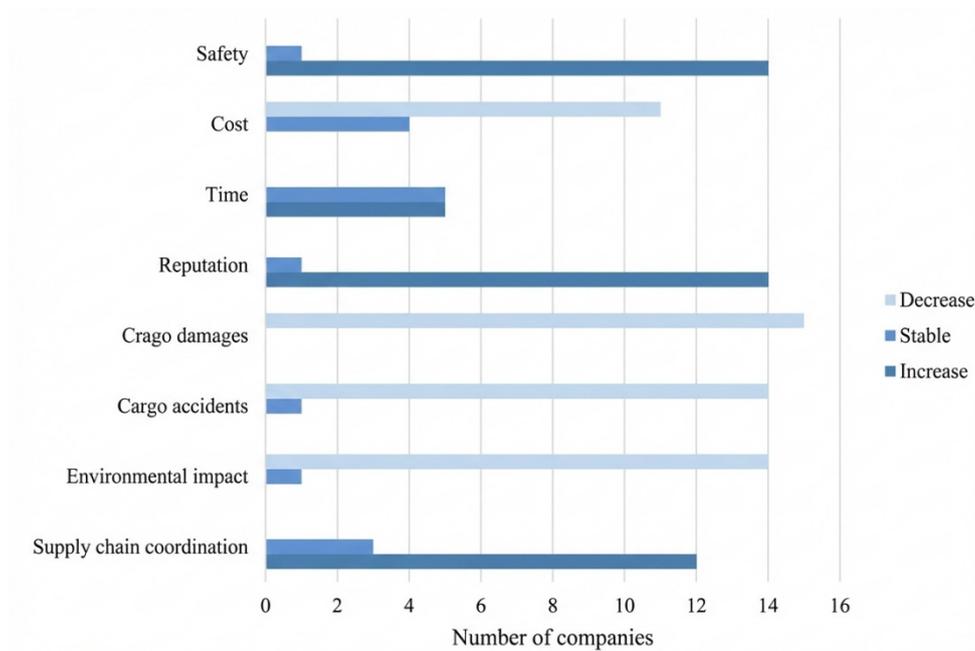**Figure 6.** Overturning of the mechanical model [26].

Figure 7. Impact generated by applying the CTU code [28].

Besides, the current debates in the Marine Environment Protection Committee indicate the long-standing problem of marine pollution by sunken containers, which further underlines the necessity of strong lashing requirements and efficient response strategies [29]. **Figure 8** provides a schematic overview of the response used to address marine pollution from shipping accidents by continuous monitoring.

Such regulatory frameworks require the continued research on dynamic load forecasting and the development of lashing materials to anticipate possible failure modes and improve the stability of containerized transport to more and more unstable maritime conditions [27]. World Shipping Council report 2025 states that it is compulsory that the entire shipping industry reports all the containers lost at sea, beginning January 1, 2026 [30]. The fact that the wall and door ends of containers have different stiffness also increases the complexity of container lashing since they deform differently and the lashing forces are also different and should be considered in the design [6].
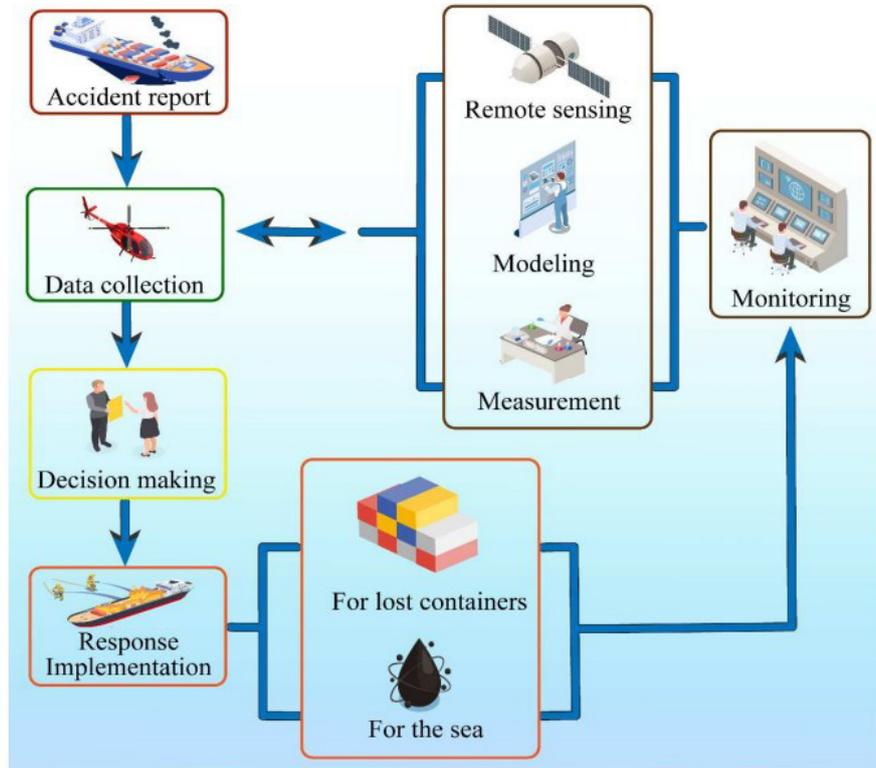
Figure 8. Response process of container ship accidents [29].

3. Design Methodologies for Lashing Systems

Container lashing system design is a complicated engineering problem and it must be approached in a multifaceted manner, combining the concepts of structural mechanics, dynamics, and material science to guarantee safe and efficient cargo transportation [31]. This is achieved by paying close attention to the forces on the container stack, including the forces of the static loads, the acceleration due to the ship movements and the environmental forces like wind and waves [27]. To optimize lashing layouts and component designs, advanced design processes frequently use numerical modelling, including finite element analysis to model the complicated interactions of the ship structure, the stack of freight containers, and the lashing gear at different operational and environmental conditions [31]. The models are frequently applied to experimental studies of scaled models to assist in the correct forecasting of

the dynamic reaction of lashing systems and optimization of their design to ultra-large container vessels [11]. **Figure 9** illustrates the methodology for construction of the scaled model.

This combined method gives useful information on the complicated physical act, which is the sliding, uplifting, and bouncing of stacked containers, which may take place even in moderate sea conditions, and enables a more precise identification of container and lashing loads [27]. Moreover, the methodologies are also important in determining the effects of large carrying capacities and container distribution on deck that may have a great influence on the stability of the ships and their safety overall [32]. The design should also consider the interests of heavy load logistics, where some types of cargo need special consideration in the choice of the appropriate shipping and loading equipment [33]. This involves the natural frequency of the hull of the ship and its response to the wave frequencies that may cause resonant responses that cause increased motions and loads on the lashing system [34].
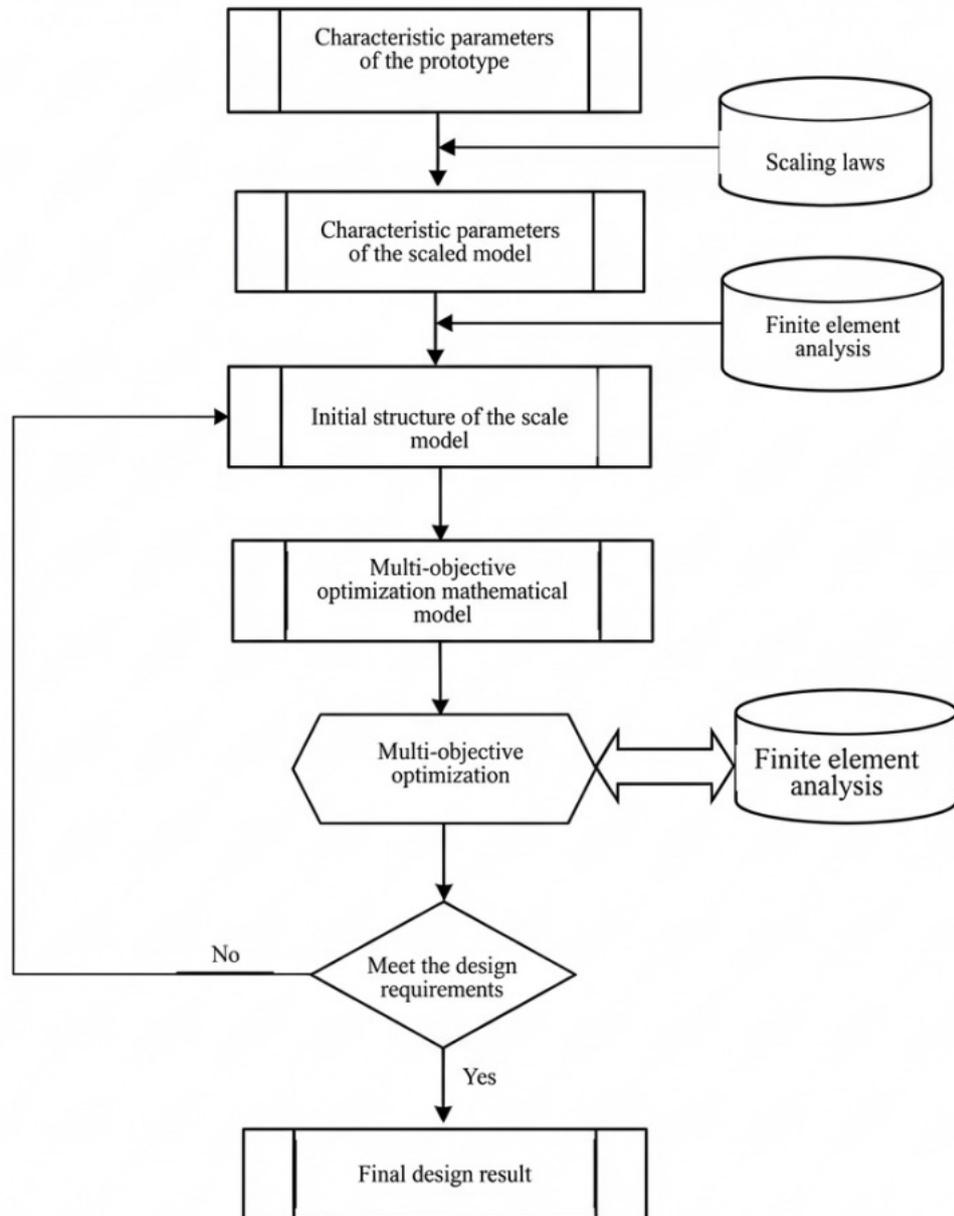
Figure 9. Scaled model construction [11].

3.1. Finite Element Analysis (FEA)

The Finite Element Analysis has been used to simulate the determination of the stress distributions, deformations and dynamic response of the complete lashing assembly under different loading conditions in detail [35]. It is a numerical technique that allows engineers to analyse the structural integrity and functionality of the lashing components, twist locks, lashing rods and turnbuckles by simulating material properties and geometry [6].

Figure 10 shows the boundary conditions and for the scaled model setup. Point masses of the containers acting vertically downwards and the point of rotation are highlighted. FEA is particularly applicable in modeling complex systems, such as the mooring system of a bulk carrier when subjected to the influence of waves, wind and currents, by developing finite element models that simulate the tension and motion behavior of the anchor chains [36]. It is also possible to evaluate global resonant vibrations using this method, taking into account hull girder bending and torsion, which are important in the interpretation of ship responses in oblique waves [37]. In

addition, FEA enables the study of coupling between the lashing bridge and hull structure, which is essential in ensuring structural design optimization, especially in ultra-large containerships [11].

Von mises stresses and the maximum shear stresses on the lashing bridge setup are illustrated in **Figure 11**. The accuracy of FEA enables the analysis of sensitive regions in which stress concentration may cause failure in detail and, therefore, the choice of materials and design changes to increase robustness. This predictive power is especially relevant to the assessment of the performance of new lashing materials and designs prior to their physical prototyping, which saves a lot of development costs and time. An example is a simplified twistlock model created with FEA, which was useful in simulating uplifting, shifting, and tipping of corner castings, which gives an insight into the non-linear behavior of lashing elements [23]. **Figure 12** shows a detailed model and the simplified model for the corner casting and the twist lock model.
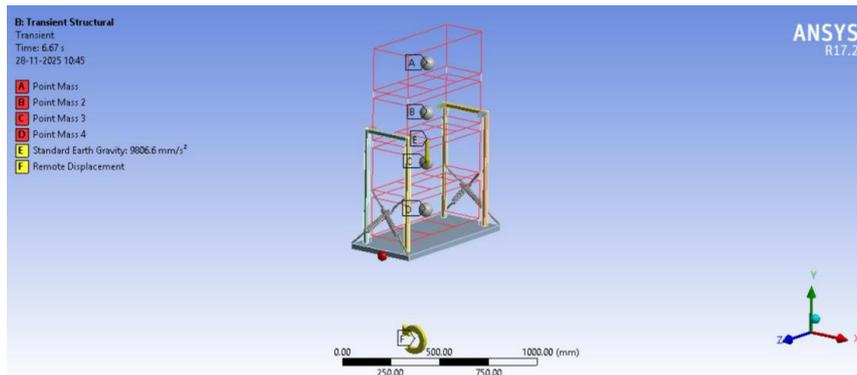

Figure 10. FEA model of system.

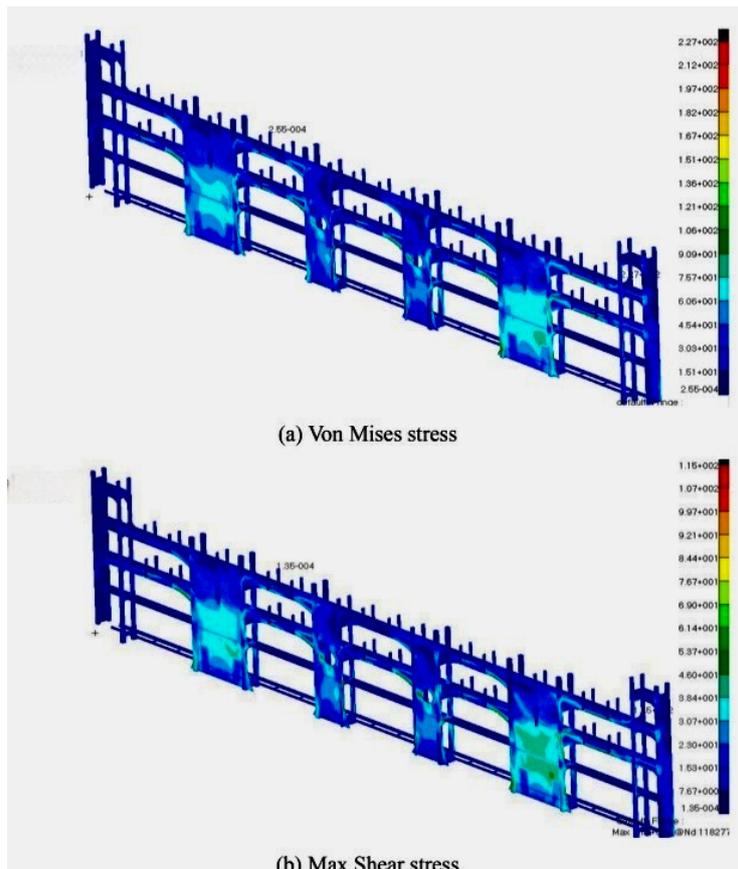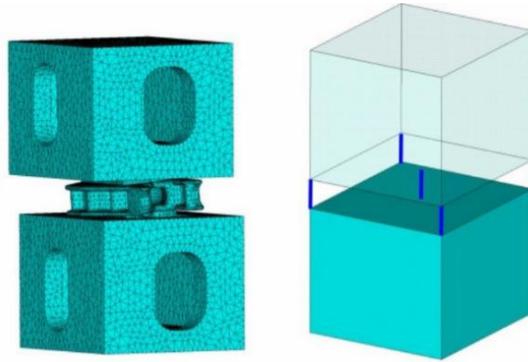

(a) Von Mises stress

(b) Max Shear stress

Figure 11. FEA analysis on lashing bridge [11].

Figure 12. Detailed model and Simplified model of twist lock assembly [23].

The rigidity of the lashing system, such as the lashing rods and turnbuckles, which are of steel with high strength, directly influences the dynamic behavior of the container stack and can be strictly studied with the help of FEA [6]. This enables the correct forecasting of forces in the lashing components, and design parameters consider the entire spectrum of operational stresses [23]. Moreover, FEA models (**Figure 13**) may include more detailed models of container structures, such as corner castings and shell elements, to better model their interaction with lashing devices and the behavior of stacks in general [23].
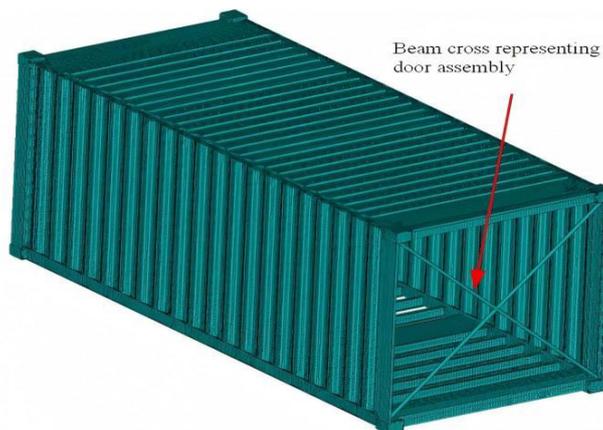
Figure 13. FEA model of a 20 ft standard container [23].

These are further developed with non-linear contact elements and spring representations of twist locks and lashing rods, respectively, to represent real-world phenomena like gaps and frictional effects between container castings [7].

3.2. Analytical Modeling

Analytical modeling, in its turn, provides a more basic method of studying the mechanics of lashing systems by simplified mathematical models, which can quickly give an insight into the behavior of a system without the computational cost of FEA. The models are most applicable in preliminary design studies and in determining some basic relationships between lashing parameters and critical responses, including natural frequencies and maximum forces. Although not as detailed as numerical simulations, analytical models can be used to effectively model the lashing system's macroscopic behaviour, including its interplay with the dynamics of the hull and cargo of the ship [11]. They frequently use simplified assumptions about material properties and boundary conditions, which permit closed-form solutions or simple numerical computations that enable quick parametric studies. As an example, the natural frequencies of mast structures on vessels have been calculated using analytical models with useful information on the possible resonance problems during ship operations [38]. **Figure 14** illustrates the eigenfrequencies and eigenmodes.
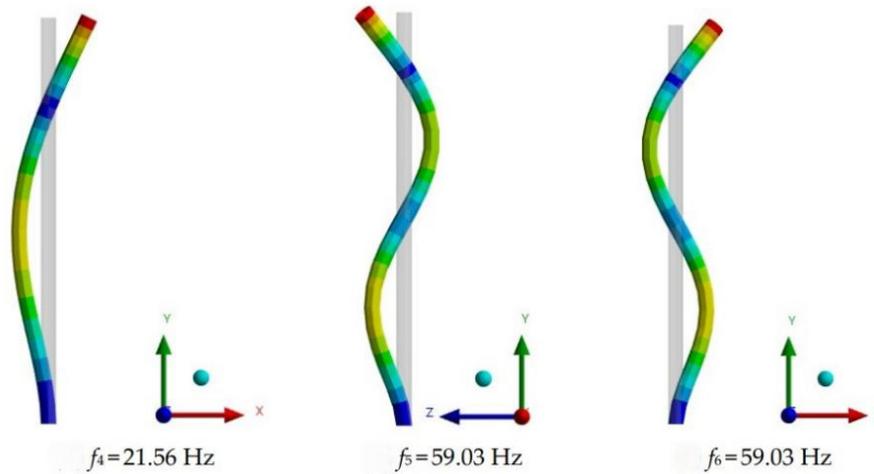
$f_4 = 21.56$ Hz $f_5 = 59.03$ Hz $f_6 = 59.03$ Hz

Figure 14. Natural modes and frequencies of mast [38].

Likewise, the models can be modified to measure the lashing system's behaviour to different motions caused by waves, which will give a fast analysis of the load distribution and possible failure points [34,39]. Furthermore, probabilistic techniques can be combined with analytical techniques to determine the reliability and safety of lashing systems in stochastic environmental conditions and give a macroscopic picture of the possible risks [40].

3.3. Experimental Testing

Experimental testing is an invaluable validation instrument of both numerical and analytical models that give empirical information, which confirms theoretical predictions and characterizes complex behavior that is difficult to model. This empirical validation is important in determining the accuracy and reliability of the simulation models, particularly considering that most of the published research works do not focus on the appropriate model validation that results in the likelihood of inaccurate results [41]. These are the tests that are usually conducted on scaled models on shaking tables in order to accurately determine the lashing forces and displacements of simulated ship motions, hence, giving the first-hand evidence of system performance [6]. **Figure 15** indicates the comparison of lashing force at door end and wall end under rolling excitation.
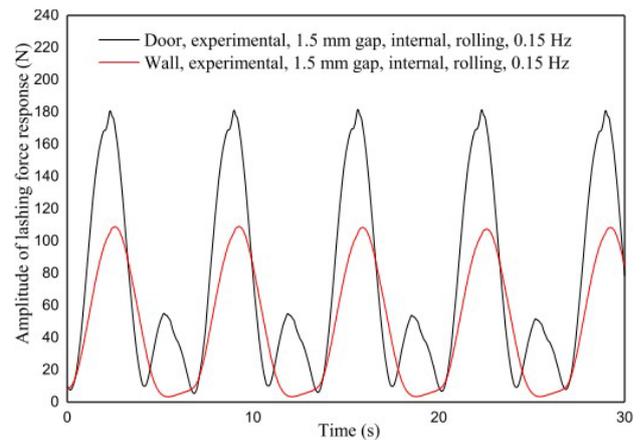
Figure 15. Vertical gap and internal lashing system [6].

These controlled environments can be used systematically to investigate such parameters as the thickness of lashing rods and other control parameters and their influence on the behaviour of the lashing bridge and distortion of containers [11]. Full-scale tests are more resource-intensive, but they give the best representation of the real-world conditions, including such phenomena as dynamic load effects and structural integrity under operational loads [42]. Moreover, experimental research using ships, like the DTC containership, can be studied in detail on seakeeping phenomena, including ship motions, added resistance, and drift forces in regular waves, which is essential in validating computational fluid dynamics models [43]. The tank tests conducted in MARINTEK's ocean basin are shown in **Figure 16**.

Large-scale model (**Figure 17**) measurements can

provide additional information on complex fluid-structure interaction problems and rare events in realistic ocean environments and thus enhance the predictive power of numerical models [44].

Figure 16. Significant non-linear behaviour observed during the tank tests conducted in MARINTEK's ocean basin [43].

(a) Model construction   (b) Launch and transportation   (c) Self-propulsion test

Figure 17. A big model used for resistance and propulsion [44].

3.4. Design Optimization Techniques

Design optimization tools use the experience of analytical, numerical, and experimental tools in order to optimize the performance, safety, and cost-effectiveness of lashing systems in a systematic manner. These methods include the systematic manipulation of design variables to obtain desired goals subject to a number of constraints, and may use algorithms to search the design space effectively. This strategy guarantees that the lashing designs that are created are not only strong in dynamic loads but also reduce the amount of material used and the complexity of manufacturing. An example is that multi-objective optimization can be employed to trade off competing requirements, e.g., the maximization of lashing strength and the minimization of weight, leading to more efficient and sustainable designs. It is also possible to use finite element analysis in conjunction with advanced optimization techniques, e.g., genetic algorithms or particle swarm optimization, to optimize the geometries of the lashing components and the choice of the materials to be used to achieve optimal performance under a wide range of loading conditions [7]. **Figure 18** shows the mathematical model developed
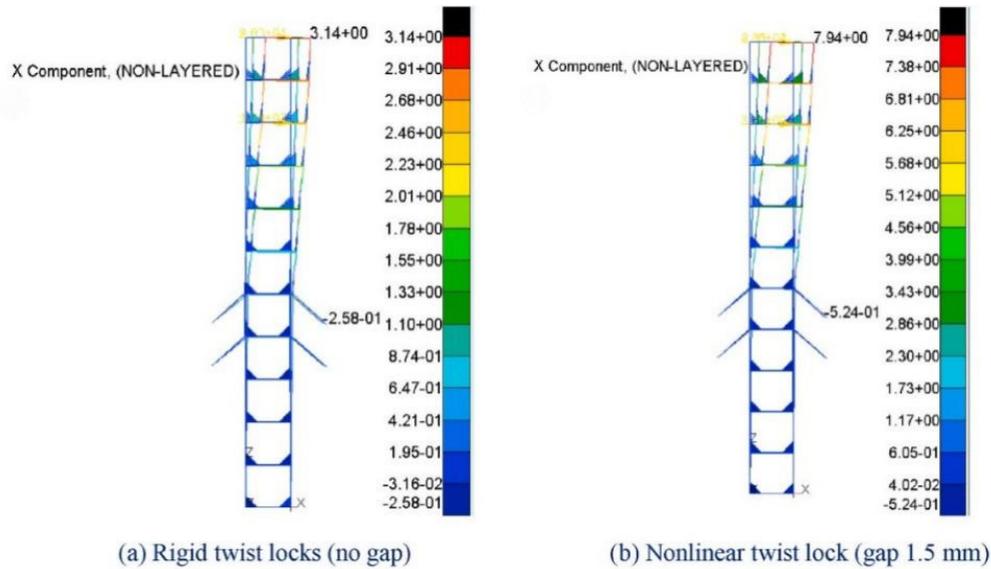
on the Veristar lashing software for studying the wind forces and the weight distribution of the stacks.

Figure 18. Calculation model made on Veristar Lashing Software [7].

In addition, the methods can apply probabilistic methods to take into account the uncertainty in the environmental conditions and material properties to enhance the reliability and safety of optimized lashing designs in the actual operating conditions [45].

3.5. Multi-Physics Coupling for Fluid-Structure Interaction

More and more recent research has utilized the techniques of multi-physics coupling in order to more accurately model the interaction of the forces of waves, fluid forces, ship movements, container stacks, and lashing components. The computational fluid dynamics (CFD) simulations are used under these approaches in the determination of the wave pressures and hydrodynamic loads on the ship and container structures that are subsequently transferred to the finite element analysis (FEA) models to determine the structural response. This fluid structure interaction (FSI) model enables realistic treatment of the influence of the boundary conditions, including the free-surface waves, roll and pitch movements of a ship, and nonlinear contact behaviour between the containers, twist-locks and lashing rods. The convergence of load-response predictions of the lashing forces under dynamic sea conditions with load-response predictions of the CFD and FEA solvers can be more accurate than uncoupled predictions of the lashing forces with either a static or quasi-static method.

3.6. Simulation Techniques in Lashing Design

The application of simulation methods is critical in design and analysis of container lashing systems, which provides an economical and efficient method of testing performance under different operational and environmental conditions without necessarily engaging in the use of large-scale physical prototyping. These computational techniques allow the engineers to forecast the complicated dynamic behaviour of lashing systems, load distribution, stress concentrations, and deformation patterns, under simulated sea conditions and cargo motions (see **Figure 19**) [7,46].

The quick estimation of extreme ship response events can be made through the application of data-driven methods, specifically Long Short-Term Memory neural networks (**Figure 20**), and can be essential to predicting peak loads on lashing systems and making design choices [47].

(a) Rigid twist locks (no gap)　　(b) Nonlinear twist lock (gap 1.5 mm)

Figure 19. Deformation of scaled container stack model [7].

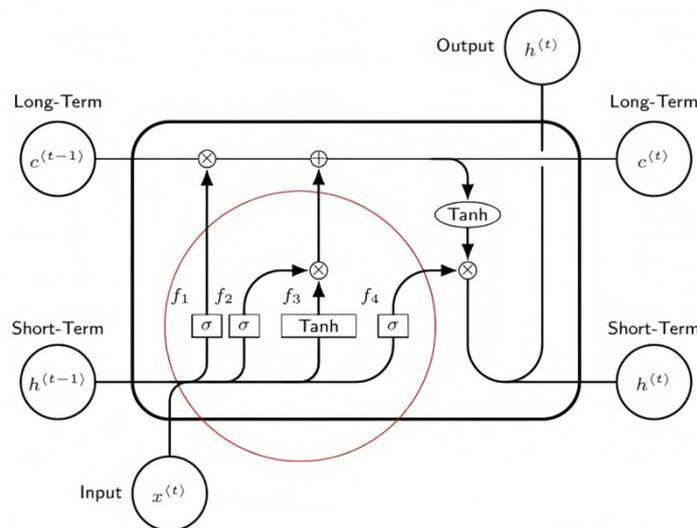Note: x: Transverse stack deformation; z: Height of the stack.

Figure 20. Basic structure of Short Term-Long Term cell [47].

In addition to predictive modeling, simulation methods, including popular Tabu Search and Simulated Annealing meta-heuristics, can also be used to address the complex stowage planning problems by optimizing cargo layout to meet stability requirements and reduce lashing forces [48].

3.6.1. Dynamic Simulation

Such techniques as CFD to model the interaction of waves and structures and FEA to model the response of structures give high-fidelity information about the complex forces that act on containers and the mechanisms that secure them [49]. This comprehensive knowledge helps to create strong lashing patterns that can resist the extreme dynamic accelerations that occur during maritime transportation, which depend on the ship's loading condition, the shape of the hull, and the speed [23]. Dynamic simulations can also be real-time measurements of accelerometers and strain gauges on vessels, and models can be continuously optimized and adjusted to the real operating conditions and forecast potential lashing failures [23]. **Figures 21** and **22** show

the multi-stack deformation and the effect of the stack interaction of the corners of the container.
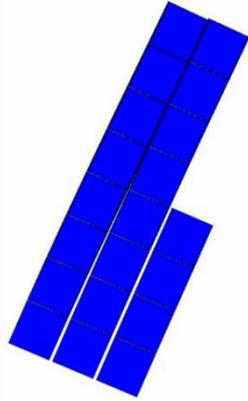

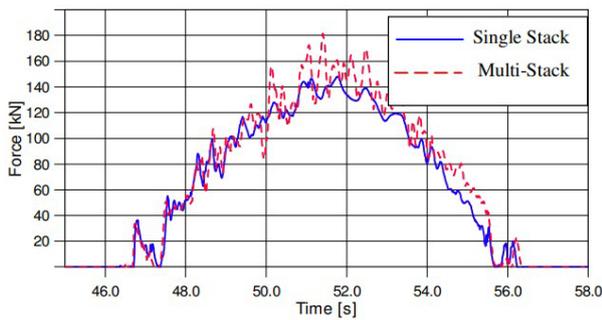**Figure 21**. Multi-stack deformation [23].

Figure 22. Stack interaction effect on container corners [23].

Moreover, these simulations are also being combined with machine learning algorithms to predict future structural behaviour and actively suggest changes to lashing setups [50].

3.6.2. Motion Analysis

Motion analysis (**Figure 23**), which is an important part of dynamic simulation, is concerned with the description of the complex motions of the ship and the stacked containers, which directly affect the loads on the lashing system [9].

This is usually done using advanced numerical models, like composite sine wave-based or hybrid neural network-based, to reliably forecast multi-dimensional ship motions (**Figure 24**), including longitudinal, transverse, and vertical waves, even in rough sea conditions where non-linear processes are imminent [51,52].
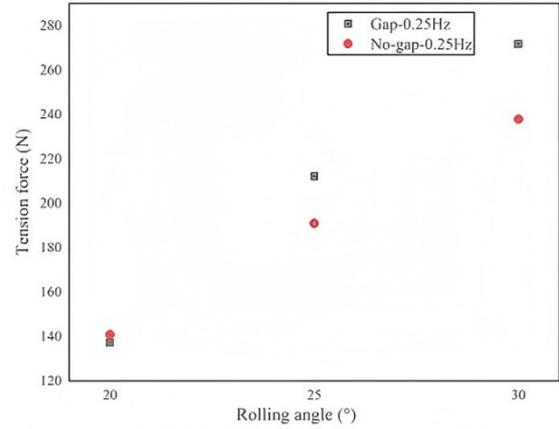
(a) Rolling angle
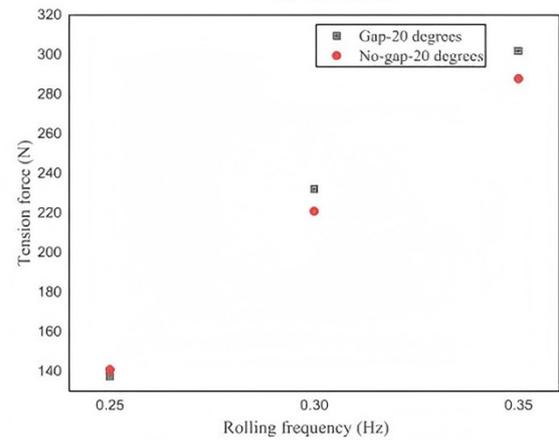
(b) Frequency

Figure 23. Effect of rolling angle and frequency of the lashing system [9].
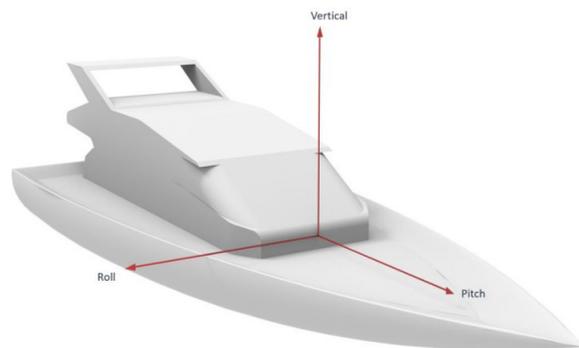

Figure 24. Illustration of ship motions [51].

These are the anticipated motions, especially rolling and pitching, which are essential inputs to the precise assessment of the accelerations on stacks since they are usually the primary reasons for container loss and structural damage [49]. Proper forecasting of these motions is the most important because improper cargo securing may cause cargo movement, which may

cause more risk of capsizing of the vessel, particularly when the vessel is changing course rapidly or when the weather is unfavourable [1].

3.6.3. CFD Analysis

Software Tools for Simulation

The analysis of computational Fluid Dynamics (**Figure 25**) is an effective method to model the complicated fluid-structure interactions that affect the performance of lashing systems, especially in the interpretation of the wave-induced loads and sloshing. The technique can be used to study the distribution of pressure and flow separation around the hull and containers of the vessel in detail, which is important in the optimization of hydrodynamic efficiency and the

alleviation of extreme forces on the lashing system. Engineers may assess the structural integrity of lashing components under actual fluid dynamic loads by combining CFD with finite element analysis, which enhances designs to make them safer and more resilient. The experience of CFD simulations is especially useful in assessing the efficiency of lashing systems in extreme weather conditions, where the impact of waves and green water on deck can cause significant forces that cannot be easily estimated by more simplistic analytical models [27]. To illustrate, CFD frameworks that involve multi-phase fluid models are required to capture the physics of sloshing in partially filled tanks that may cause substantial dynamic forces on the container walls and their fixing systems [53].
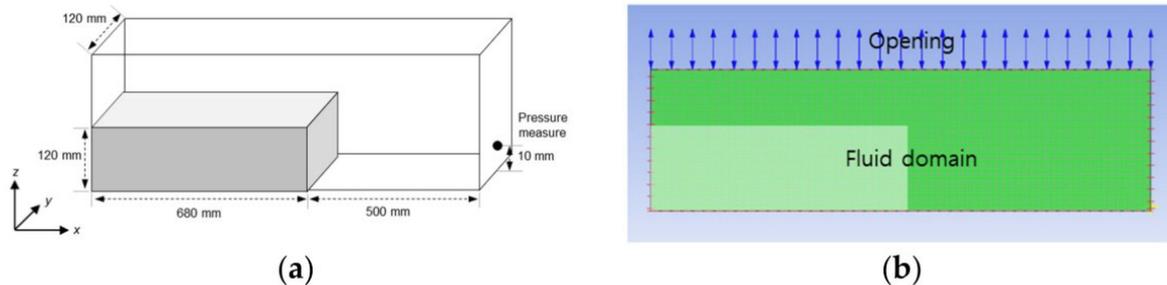

Figure 25. Experiment and CFD model [53].

4. Critical Parameters and Performance Metrics

The performance of container lashing systems is measured using a number of key parameters and performance measures that determine how well they can ensure the integrity of the cargo and avoid the loss of containers during transit. Such measures usually involve the maximum lashing force, container stack stability and dynamic reaction of the securing system to different sea states and operational conditions [31].

Some of the key performance indicators include the assessment of the final tensile strength of the lashing components, the distribution of the loads between several securing points, and the ability of the system to withstand sudden impacts or resonant frequencies. Also, the difference in lashing force caused by the difference in the rigidity of the container ends, i.e., door

and wall ends, is a crucial issue that affects the overall container security and load distribution [6]. Moreover, the dynamic amplification factor, which considers the inertial effects and oscillations of the lashing system during the wave-induced motions, is an important measure of the capacity of a system to resist the peak loads that are much higher than those obtained by the static calculation (**Figure 26**) [6]. **Figure 27** illustrates that, in case of bottom twist-lock, the tensile force in internal lashing is remarkably greater than that of external lashing.

In addition, these measures are usually compared to international standards, like the ones established by the IMO, to guarantee adherence and improve international maritime safety standards. **Figure 28** shows the comparison of the bottom twist lock force at door end and wall end.
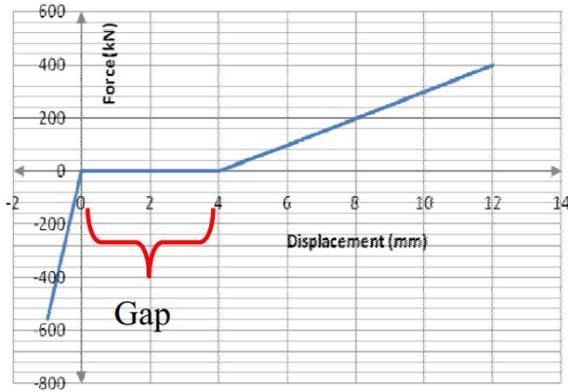
Figure 26. Behaviour of non-linear spring for twist-lock and corner casting connection [31].
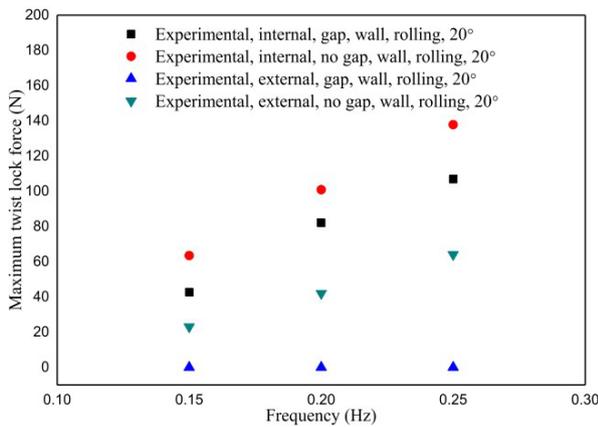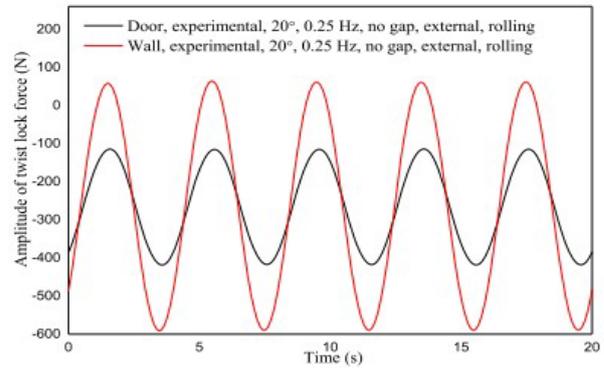

Figure 27. Comparison of twist-lock tensile force for variable frequency [6].
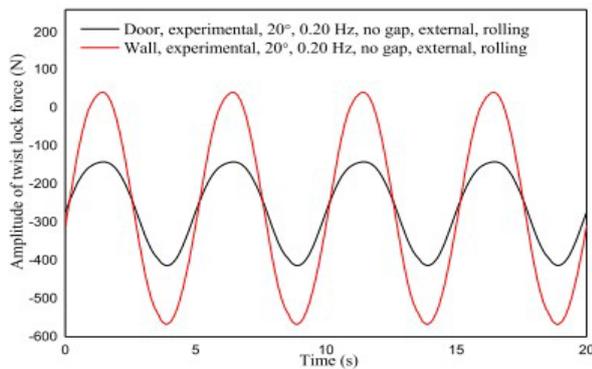
(a) Case: 20°, 0.20 Hz

Figure 28. *Cont.*

(b) Case: 20°, 0.25 Hz

Figure 28. Experimental time-history of twist-lock forces at the door-end and wall-end under rolling motion at 20°: (**a**) 0.20 Hz and (**b**) 0.25 Hz, showing inherent experimental variability [6].

4.1. Lashing Tension and Stress Distribution

The parameters of lashing tension and stress distribution are the basic parameters in the evaluation of structural integrity and dependability of container securing systems that have a direct impact on the ability to resist the dynamic loads that are experienced during sea voyages. These forces are extremely important to measure and predict, as they determine the likelihood of the lashing component failure and container loss. These parameters are especially important because the lashing forces may vary considerably, and the maximum loads are usually concentrated in the door end of the container because of the structural difference [6]. **Figure 29** shows the linear deformation the lashing assembly with the applied force.

This entails a lot of knowledge on how the rigidity of the different parts of the container, cargo setup and stacking depth affect the transmission of load using the lashing system [11]. Thus, experimental values of the lashing force that is frequently calculated with the help of force sensors installed in the strategic points on lashing elements are priceless in the context of the validation of the numerical models and optimization of securing arrangements [6]. **Figure 30** shows the locating

points of the force sensors on the experimental setup.

The intricate relationship between the weight distribution in containers, the declared weight of the cargo, and the dynamic stress of the lashing components is further supported by these experimental results and the numerical analysis [4]. The combination of this approach will enable a better analysis of the load transfer processes in the container stack and securing system, which will assist in enhancing safety measures and design.
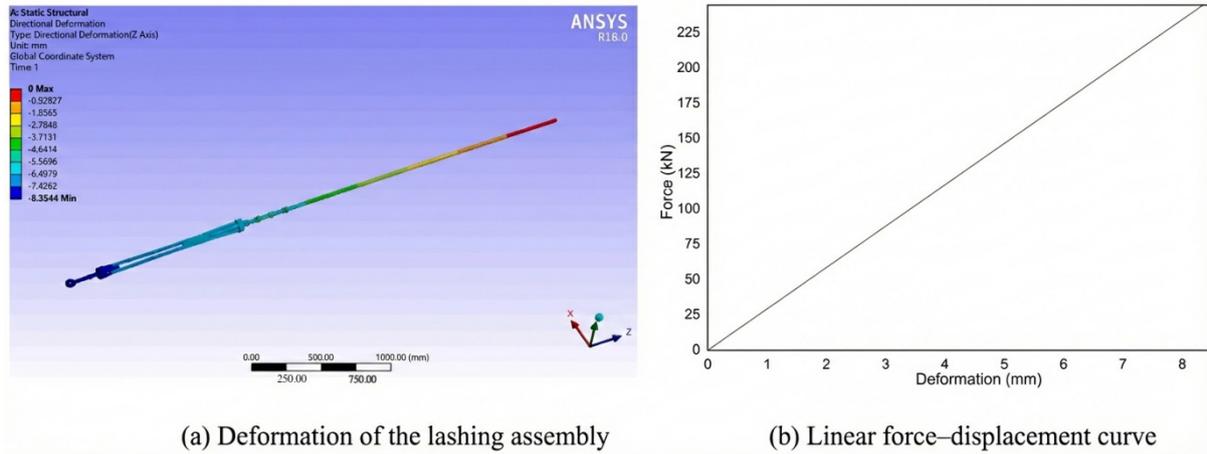

(a) Deformation of the lashing assembly (b) Linear force–displacement curve

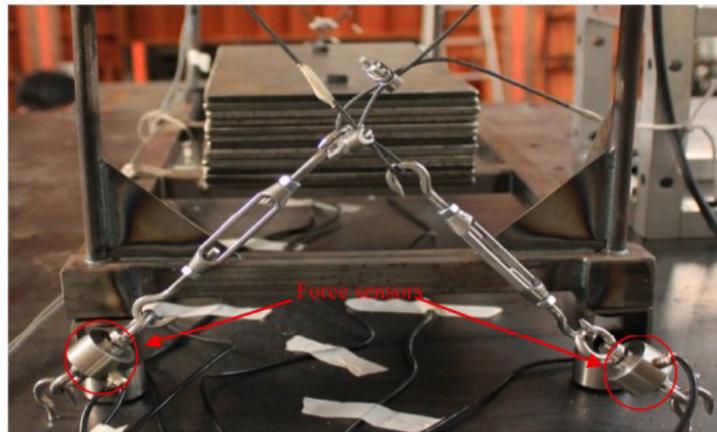**Figure 29**. Lashing assembly stiffness [6].

Figure 30. Position of force sensors [6].

4.2. Container Displacement and Acceleration

The main output parameters that will directly show the effectiveness of a lashing system in minimizing cargo movement and loss of containers during dynamic ship movements are container movement and acceleration, as shown in **Figure 31** [6].

The dynamic behaviour of rocking, sliding and jumping of the containers at various accelerations of the vehicles is significant in designing lashing and stability of cargo [8]. **Figure 32** shows the possible package motion states after collision.

These parameters are particularly important to assess the risk of the loss of containers in the sea that, even with the efforts of the industry, is a serious problem [5]. Moreover, accelerations can be excessive, which can lead to large loads on the lashing system, which can cause material fatigue or catastrophic failure [54]. On the other hand, tracking the movement of containers enables the engineers to ensure that the lashing system is effective in limiting the movement within reasonable limits to avoid collisions of containers or damage to the ship structure.
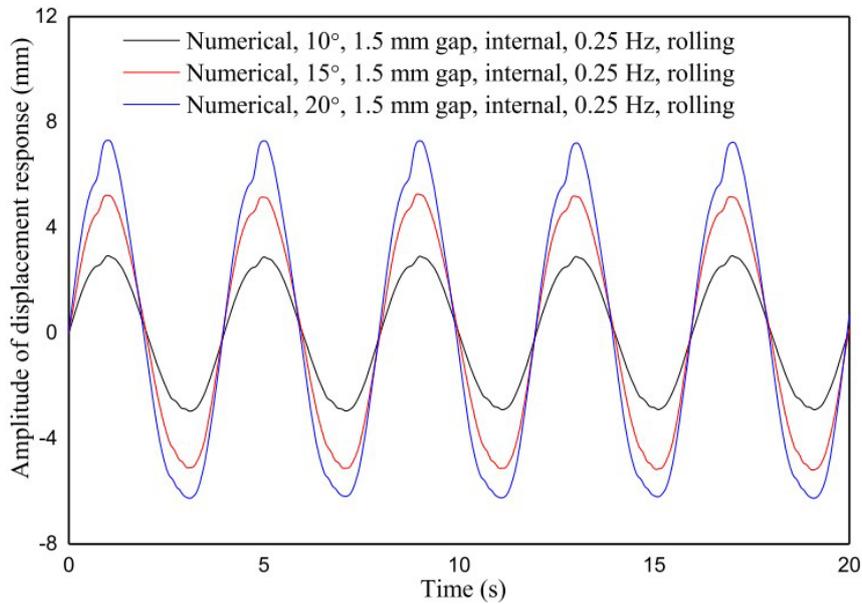
Figure 31. Time-history curve of vertical gap system displacement [6].
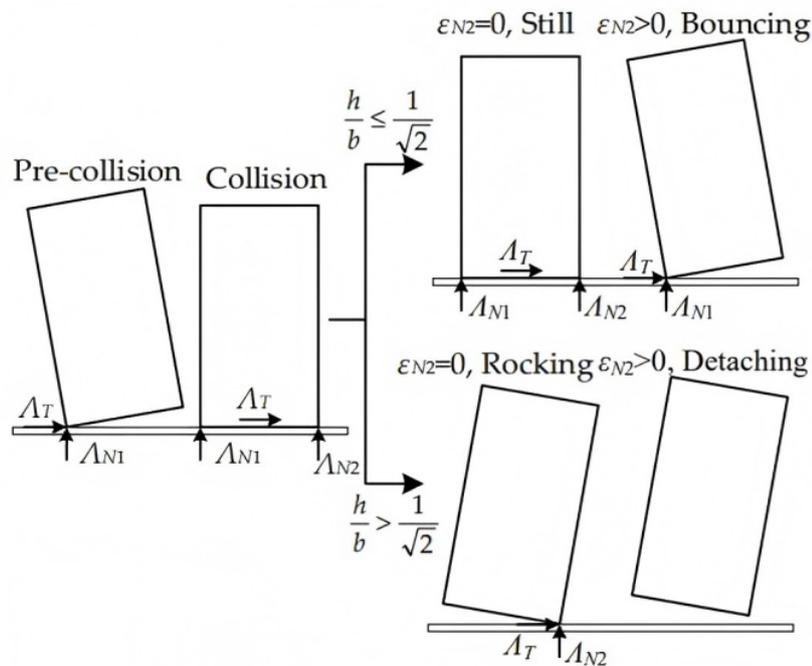

Figure 32. Possible motions after collision [8].

4.3. Fatigue Life and Durability

The life and durability of fatigue are the most important factors to consider when designing and maintaining lashing systems because these components are exposed to cyclic loading, which may cause degradation of materials and eventual failure with time. The cyclical loading is mainly influenced by the constant motions of the ships and the forces of the environment, which require designs capable of withstanding millions of stress cycles without structural failure [11]. **Figure 33** illustrates the model test and the frequency response curve.

It is therefore important to predict the remaining useful life of lashing components using fatigue analysis that takes into account factors such as material properties, stress concentration points and environmental

corrosion, as a proactive measure to maintenance and replacement. In addition, dynamic forces, material properties and environmental factors, such as corrosion and abrasion, can significantly affect the long-term integrity of lashing systems, and may significantly enhance the rate of fatigue crack initiation and propagation. Hence, the intensive testing and sophisticated simulation process, including the finite element analysis including fatigue models is necessary to compute and estimate the life and reliability of the lashing systems under the real operating conditions. It is a comprehensive design and analysis approach that ensures that the lashing systems are not only in a position to meet the immediate operational needs but also has a long service life thus eliminating the risks that are presented by container transport [2]. The dynamic stresses, particularly the stresses enhanced by resonance effects, and the accruing effects also warrant the consideration of designs that combine high-cycle fatigue resistance and robust material selection [14].

4.4. Safety Factors and Risk Assessment

Because they offer a methodical approach to evaluating the possible risks and uncertainties in the design and operation, the components of safety and risk analysis are implicit to the dependability and operational safety of the container lashing systems. These are usually incorporated by incorporating conservative multipliers to establish loads, material strengths, and therefore they serve as a buffer to the unknown conditions, the nature of cargo, and human factor which are usually difficult to predict with certainty. Furthermore, more probabilistic risk assessment methods based on the statistical distributions of loads and resistances are now increasingly popular to provide a finer view of the likelihood of failure, complementary to deterministic safety factors. This allows a more thorough evaluation of the likelihood of the lashing system failure under various working conditions and ultimately makes more reasonable design decisions and working policies [10]. **Figure 34** shows the different techniques for securing the loads.

(a) Modal test

(b) Frequency domain curve
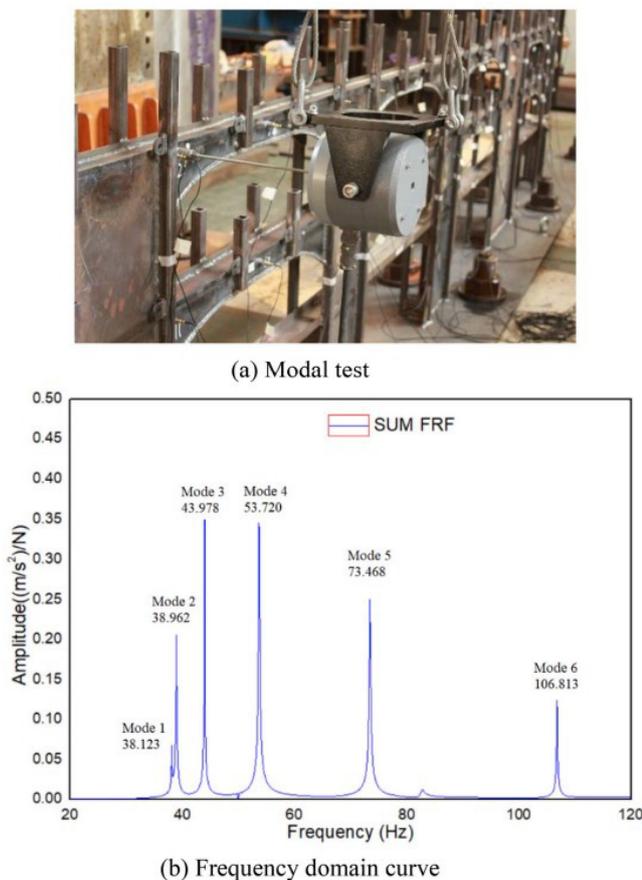
Figure 33. Modal analysis of lashing bridge [11].

Figure 34. Common load securement techniques [10].

The complications of extreme weather events demonstrate the weakness of traditional classification rules in defining the sufficient lashing design values, which makes it necessary to consider more advanced risk assessment models that consider dynamic factors [6]. These sophisticated models are especially essential considering that extreme weather conditions are one of the main reasons for high loads on container stacks

and lashing systems, which result in container loss and damage [7].

5. Challenges and Limitations of Current Methods

Although there have been considerable improvements in design and simulation techniques of standard freight container lashing, there are still a number of challenges and limitations, especially in the ability to capture the complex dynamic processes and interactions with the environment. Such restrictions are usually due to simplification of complex phenomena, including non-linear material behaviour, fluid-structure interaction and stochastic nature of environmental loads, which can cause differences between simulated predictions and actual performance in the real world [9,55].

Figure 35 shows the result of variation in the twist-lock gap on deformation. To illustrate this, the interaction between the lashing bridge, container stack and hull structure has never been recorded in most studies and they are usually taken independently, and this can lead to the inaccuracy of prediction of dynamic responses [7]. This stiffness contrast between the lashing bridge and the hull structure may have a strong impact on structural responses and force distribution and needs integrated evaluation methods that take into account this coupled behavior [7]. Besides, the increasing size of container vessels and the resulting increase in the height of container stacks contribute to the challenges, introducing new inertial forces and more complex dynamic interactions within the lashing system [11].
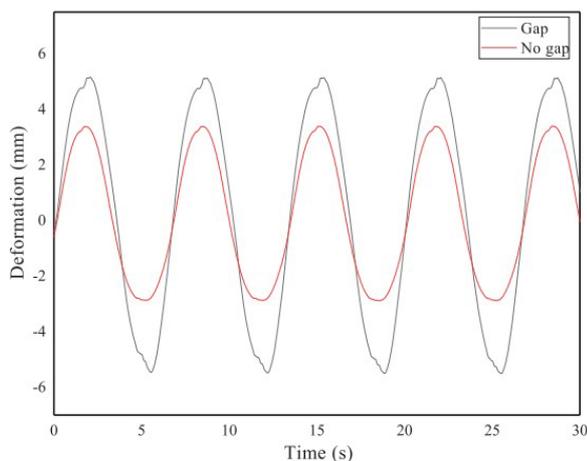
Figure 35. Effect of gap on container stack deformation [9].

5.1. Accuracy of Simulation Models

Predicting the behaviour of lashing systems under different operating conditions requires accurate simulation models, but these models' authenticity is usually jeopardised by their inherent simplifications and the computing difficulty of simulating intricate, non-linear interactions. This is especially evident in the difficulty of accurately modelling phenomena that are very sensitive to even the smallest changes in input parameters and external variables, such as friction, material yielding, and fatigue propagation [11]. The scaled structural vibrations curves are plotted in **Figure 36**.
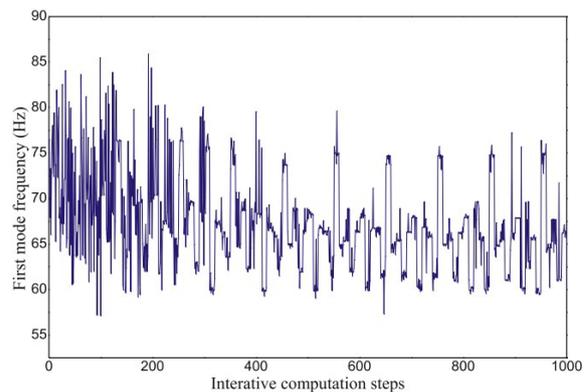
Figure 36. First mode frequency curve [11].

Numerical models are made more difficult by the discrete dynamics of container stacks, which are made up of numerous interacting bodies. In most cases, specialised algorithms are needed to mimic the intricate force transfer and movement by the lashing system [31]. Moreover, the high cost of high-fidelity computations, especially of large container vessels with numerous lashing points, may often involve trade-offs between model complexity and practicability, thereby impacting the accuracy and external validity of the results.

5.2. Complexity of Dynamic Loads

The actual depiction of the dynamic loads, particularly the extreme sea conditions is a challenging task due to its transient and stochastic nature, and most of the time non-linear, which can be resonant and amplifying forces in the lashing system [7]. This is further complicated by the fact that the stiffness of lashing assem-

blies and bridges can be very different in comparison to the classification society and more experimental and numerical analysis is needed to predict the dynamic response with appropriate precision [7]. **Figure 37** shows the time history curve of dynamic responses between two measuring points.

Other dynamic effects are driving excitation and twist lock gap, which can significantly alter the dynamic response of the displacement of the container and the lashing forces [6]. The non-linear behaviour of the con-tainer stack, lashing system and ship hull can necessitate the use of advanced numerical models, such as finite element analysis using multi-body dynamics, to find reliable predictions of these dynamic responses [6,7]. The calcula-tion of correct design accelerations and the assessment of loads on container stacks are vital in the safety and re-liability of lashing systems, particularly when the accel-erations on container ships are higher in parametric roll situations [22]. **Figure 38** show the gravity acceleration components responsible for the roll angle.
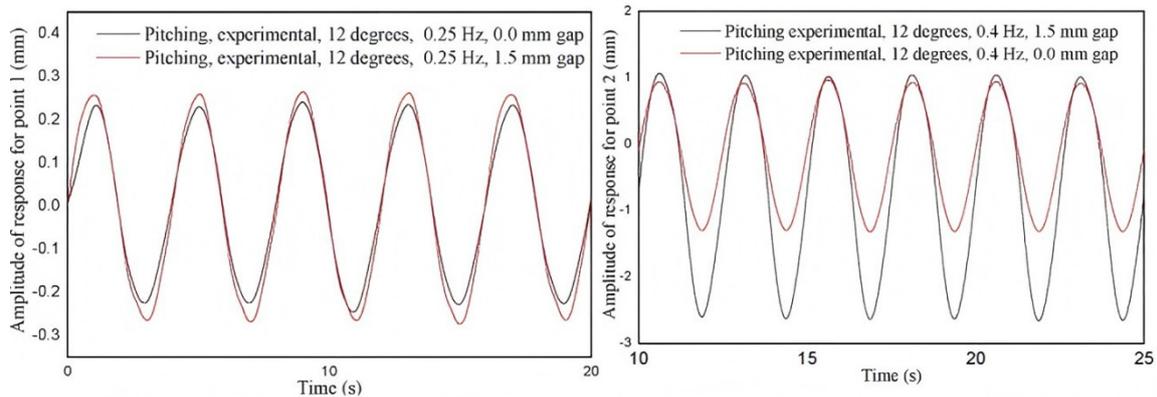
(a) Longitudinal deformation at point 1

(b) Longitudinal deformation at point 2

Figure 37. Gap-induced dynamic reaction of the container stack and lashing bridge [7].
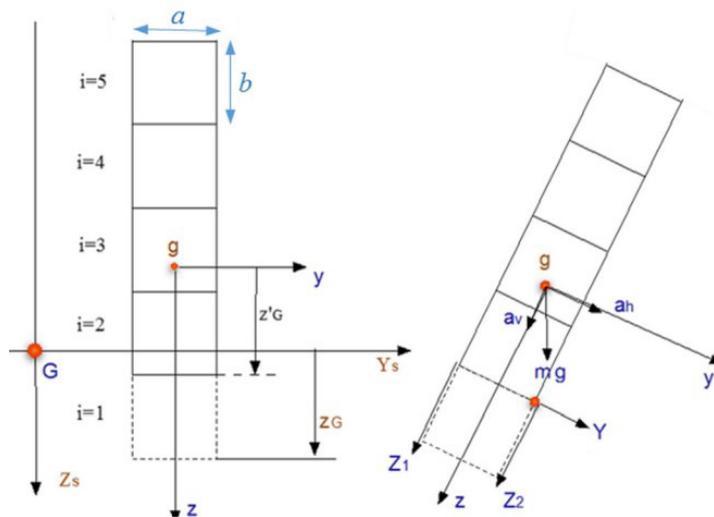
Figure 38. Conventional arrangement of container stack forces [22].

5.3. Material Behavior Uncertainties

Mechanical properties of lashing materials, in-cluding steel cables, turnbuckles, and twist locks, are inherently variable, subject to environmental degrada-tion, and manufacturing tolerances, and present seri-ous uncertainties to design and simulation work. The uncertainties are also complicated by the fact that plas-

tic deformation and fatigue damage may occur during cyclic loading, and thus progressive degradation of material properties with time may occur, requiring strong models of material characterization and damage accumulation [11]. **Figure 39** illustrates a detailed view of the lashing system connection points.

Moreover, the contact between various lashing elements, including the twist lock and the lashing rod, and the material behavior of the elements to dynamic loads should be carefully studied in order to guarantee the integrity of the entire system [6]. This demands advanced material models that can be able to take into account viscoelasticity, plasticity and fracture mechanics at different temperatures of operation and corrosive environments. These models are more likely expected to be probabilistic in nature so that the impact of uncertainties in the material properties can be quantified on the system reliability and safety margins in general when the system is brought to extreme conditions. Moreover, the determination of the uncertainties of the condition of the system is critical to the achievement of reliability-based marine activities and the powerful lashing design [56]. **Figure 40** illustrates the recursive flow of the suggested algorithm that consists of the weather updates, sigma-point calculation, system propagation and measurement updates to adjust vessel and sea states parameters at the same time and quantify their uncertainties.

(a) Lashing rod-corner casting connection (b) Details of the lashing components in test
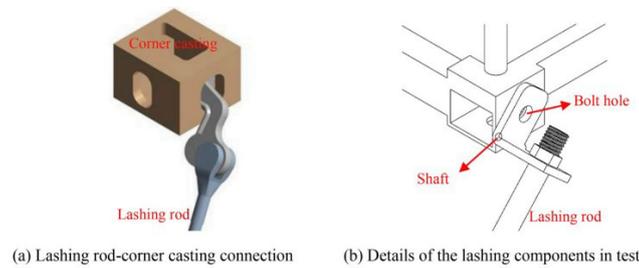
**Figure 39**. Details of corner casting and lashing rod [11].
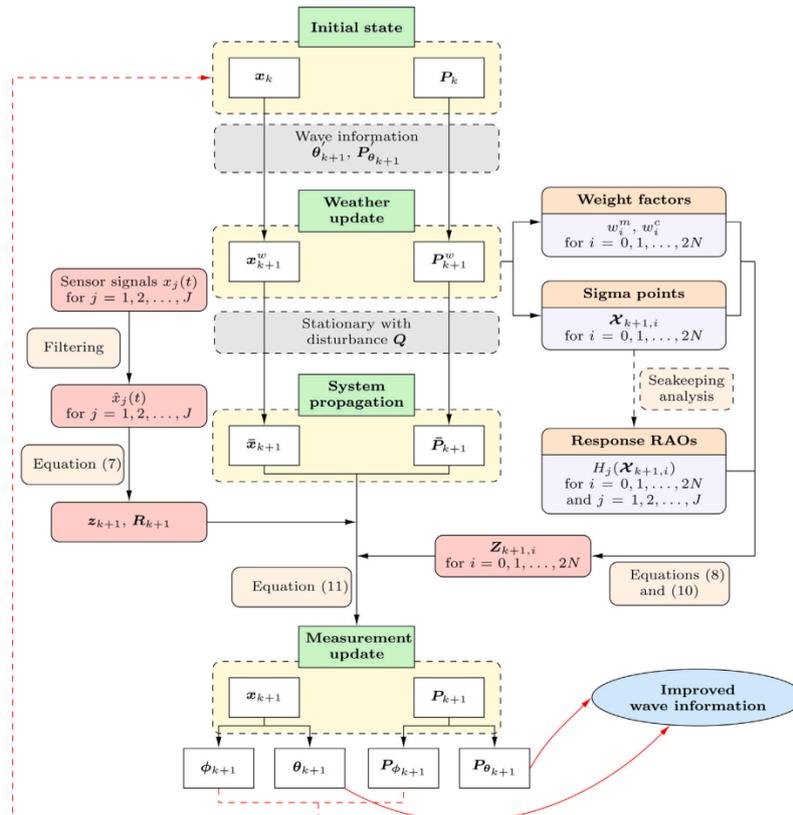
Figure 40. The process of adjusting sea state features and vessel settings while quantifying uncertainty [56].

The complex models must also consider the fact that the materials may age and degrade as the service life is long, which may compromise the structural integrity of lashing components. This general understanding of the material behavior is essential in the development of predictive models that are effective in assessing the long-term behavior and useful life of lashing systems, thereby minimizing the likelihood of failure during maritime transportation [57].

5.4. Computational Costs

The computational expense of high-fidelity simulations of complex lashing systems, such as those with multiphysics interactions and large parameter sweeps, may be a major impediment to their use in practice in design and analysis. This is more so in dynamic simulations, which are fluid-structure interaction, wave-induced motion and non-linear material response, which require a lot of computational power and time to converge and achieve a reasonable accuracy [6]. This, in turn, necessitates the use of simplified models or surrogate modeling methods to handle such computational costs, at the cost of resolution and predictive capability in many cases [11]. **Figure 41** displays the testing setup and the measuring points on the test setup.
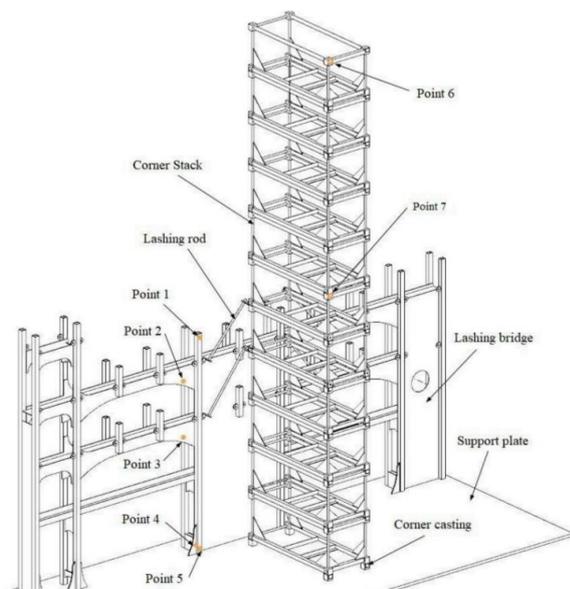
Figure 41. Dynamic motion test model [11].

This constraint frequently requires a trade-off between the level of detail desired and the ability to get timely simulation results, thus affecting the extent and intensity of design optimizations. Moreover, the need to have high-performance computing infrastructure and special software licenses only increases the economic burden, and extensive simulation-based design is only affordable to the largest organizations. Nevertheless, with the development of computational techniques, including reduced-order modeling and machine learning algorithms, there are promising opportunities to overcome the computational requirements and still achieve reasonable accuracy and predictive power of lashing system analysis.

6. Conclusion

The paper has provided an overall review of the design and simulation techniques used in the standard freight container lashing and the complexity of the problems involved in the proper modeling of these complex systems. It has highlighted the imperative of the development of sophisticated simulation methods that can be used to model dynamic loads, material uncertainties, and cost limitations to guarantee the safety and reliability of container transport. It should be studied in future to develop combined computational models that can combine the multi-physics simulations with uncertainty quantification techniques to provide more reasonable predictions of the performance of the lashing system under various operational and environmental conditions. Virtual prototyping, based on multidisciplinary integrated systems modeling, requires further development to ensure the overall system performance is maximized and the cost of development is minimized in the case of stochastic environmental loads [58]. In addition, the integration of the real-time monitoring data and the simulation models based on the idea of digital twins could enable the creation of adaptive lashing methods that can dynamically respond to the evolving sea conditions and the state of the cargo [12]. This would not only provide some safety margins, but would also help in streamlining the operations of handling the cargo, besides making the operations less risky. Even more

importantly, predictive maintenance and early warning of possible lashing failures that may be brought about by the implementation of machine learning algorithms into such digital twins may help to make the safety and operational efficiency even more improved. The recent trend of the growing size and speed of container ships has only served to increase the demand for better lashing designs that are capable of sustaining the growing harsh environmental loads and can accommodate a variety of cargo designs [7,59]. This requires further attention on the creation of more precise predictive models and experimental verification techniques to meet these changing requirements and guarantee the security of containerised cargo [6].

6.1. Summary of Key Findings

It was found that the available simulation techniques had serious problems with the ability to simulate the nonlinear dynamic behavior of lashing systems, and especially when using extreme sea conditions and non-uniform cargo distributions. It marked the importance of using the latest material modelling that considers viscoelasticity, plasticity, and fatigue and the importance of having sound uncertainty quantification techniques to enhance the reliability of the lashing plan. Further, the review had identified a significant lack in the discussion of hull flexibility and dynamic behaviour of container stacks, and more detailed models are needed to integrate ship-structure interaction with lashing system dynamics [6]. By providing a high-fidelity, real-time virtual simulation of the actual lashing system, digital twin technology presents an opportunity to overcome these issues [60]. This would make it possible to implement active lashing schemes, preventive maintenance, and ongoing monitoring, all of which would maximise cargo safety and operational efficiency during the trip. Moreover, the integration of the most recent data analytics and machine learning solutions with digital twins will be able to predict the lashing forces distributions and enhance stowage plans in real-time, which can also help to significantly increase the safety and efficiency of operations [13].

6.2. Recommendations for Future Research

The next generation of research ought to focus on creating multi-fidelity modelling techniques that can be used to integrate high-fidelity models of the key components with simplified models of the less sensitive regions to maximize the allocation of computational resources without affecting the accuracy. This method may combine the lashing gear component's detailed finite element analysis with macro-element container stack models, providing a trade-off between the cost of computation and model accuracy. Moreover, the gap effect, especially in twist locks, and its impact on the distribution of loads in the container stack and lashing systems, are still of significance to the improvement of the model accuracy [11]. In particular, the nonlinear dynamic coupling effects between the twist lock forces and lashing forces, particularly in different excitation conditions, should be further elaborated [6]. Also, the investigation of the effect of other lashing materials and designs, in particular, the ones that incorporate smart technologies to adjust tension in real-time, may result in new solutions to improve cargo security. Besides, the ongoing development of new sensor technologies and Internet of Things will assist in accumulating new volumes of real-time operational data, which can be further used to test and optimize the current simulation models and make more accurate predictions about the lashing system behaviour. Within the framework of container lashing, further studies of the application of virtual environments and digital twins, as in the example of port operations, can allow more advanced predictive maintenance and operational planning, which will enhance safety and fuel efficiency [61]. The latter are necessitated by the fact that maritime logistics is getting increasingly complex, and it requires new methods of globalisation, digitisation, and sustainability [62]. The changes in lashing will be determined autonomously due to the artificial intelligence and machine learning algorithms incorporated into these predictive models, which will decrease human error and enhance the safety of cargo in transit. It would also involve the straightforward incorporation of predictive models into maritime logistics and the establishment of standard-

ized data exchange and interoperability models across different simulation platforms and systems of operation. Also, the increase in predictive analytics studies to streamline port operations, vessel arrival and departure schedules, cargo handling, and other factors can make a significant difference in lashing plans [63,64]. The next research directions in this area should be on the development of high-fidelity digital twin systems that integrate real-time sensor measurements with numerical simulation models to track and predict the lashing forces during the operation. Machine learning methods that are being trained on experiment and operational data can also be used to improve predictive accuracy and adaptive lashing strategies. As well, full-scale and advanced scaled-model tests are required to quantify the uncertainties and warrant the dynamic load factor in the future regulation standards.

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Conflicts of Interest

The authors declare no conflict of interest.

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