



## **TopTier**

### **Overall summary report**

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# TopTier

## Overall summary report

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## EXECUTIVE SUMMARY

The Joint Industry Project (JIP) consortium, leveraging the diverse and in-depth knowledge of its participants, has taken proactive measures to address the issue of container loss in the maritime industry. Despite the statistically small occurrence, the consortium is committed to further reducing container loss.

Over the course of 3.5 years, the TopTier project conducted extensive research, including incident analysis, interviews with ship and shore personnel, physical testing, and engagement with regulatory bodies. The project aimed to provide intuitive onboard guidance for in-design conditions, ensuring clarity, reliable monitoring, defined procedures, and comprehensive training. However, the absence of terminal operators in the JIP was identified as a limiting factor.

Key aspects associated with container loss were identified:

1. Off-design conditions like parametric roll.
2. Dynamic aspects like stack dynamics.
3. Extreme weather conditions.
4. Incorrectly stowed or mis-declared container weights.
5. Poor conditions of lashing gear and containers.

Analysis of 44 incidents where information is publicly available, revealed that parametric roll is the most likely cause of large incidents, while single bay losses are often due to local failures and stack resonance. Testing indicated that twist locks vary in holding forces, and container castings are a weak link requiring proper design and inspection. The lashing software, while essential, relies on adherence to digital stowage plans and operational decisions.

The project identified several key findings:

1. Model tests validated sea-keeping and parametric roll behaviours.
2. Container stack testing showed dynamic loads increase forces by up to 23%.
3. Model scale experiments highlighted the impact of racking and torsional stiffeners on lashing forces.

Surveys and interviews with over 1,500 sea and shore personnel revealed challenges in overseeing the container stowage plan execution and its validation, predicting vessel response to weather, and the inconsistent use of navigation software tools. The lack of standardised processes also hindered improvements.

Regulatory engagement included submissions to the IMO and interactions with ISO to revise standards for containers, corner castings, and twist locks. As well interaction with Class Societies to improve computational methodology for lashing forces.

Key recommendations from the project include:

- Implementing operational guidance for proactive avoidance of off-design conditions also in combination with Second Generation Intact Stability (SGIS) criteria.
- Harmonising performance and functional standards for onboard lashing software.
- Improving inspections of lashing gear and containers.
- Recognising the use of onboard lashing software in rules and regulations.
- Including multi-bay stack resonance effects in container securing computations.
- Address uncertainty in container stowage positions, and consider improvements to the enforcement of Verified Gross Mass (VGM) requirements.

The report provides details into the issues, research, and subsequent recommendations.

## 1 INTRODUCTION

This report contains an overall summary of the TopTier joint industry project (JIP), a participant funded collaborative initiative aiming to prevent the loss of containers at sea.

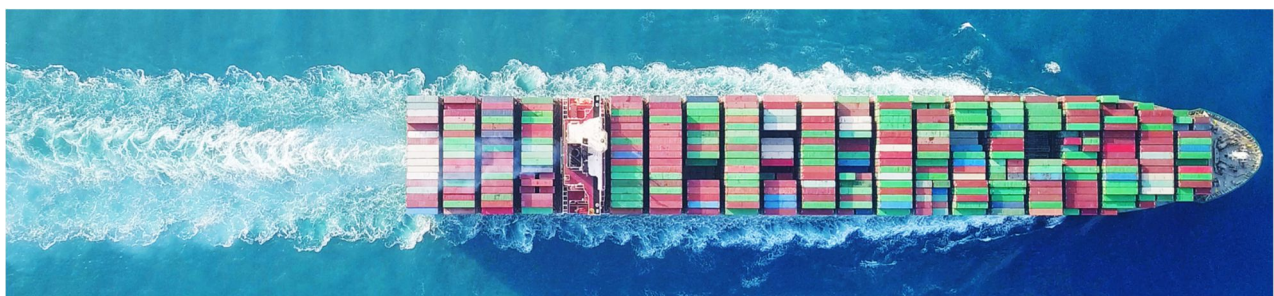
The project is supported by 43 participants including maritime administrations, major carriers, class societies, lashing gear manufacturers and system vendors, shipyards, insurance, international associations representing container carriers, container owners, cargo Insurance, and P&I, and knowledge institutes. The 3-year TopTier Joint Industry Project (JIP) started in April 2021 and concluded in November 2024.

The primary objectives of the TopTier JIP are to identify factors contributing to loss of containers at sea and recommend improvements. Conclusions from data driven, science-based research are used to increase technical understanding as is needed for safe designs and continuing innovations.

The project has been subdivided into six working groups, each dedicated to a specific bounded scope. These working groups addressed the strength of lashings and containers, stowage planning, ship motions, cargo securing loads, ship operations and regulatory considerations. These working groups contribute to the overall project goal with targets that are complementary. The tasks and findings from the work groups are listed in separate reports. A complete overview of the delivered reports and public deliverables can be found in the References section.

The aim of this summary report is to provide an overview of the project scope and findings. Target audience are all participants in the TopTier JIP, regulators as IMO, ISO and other stakeholders in maritime container transport.

The document starts with an overview of the project organisation and background information (Chapter 2), followed by an analysis of root causes related to container loss at sea (Chapter 3). In Chapter 4, each working group provides a condensed factual documentation of objective, scope and main findings. This is followed by an interpretation of integrated results, overarching the separate working groups in Chapter 5. The report concludes with recommendations that arise from this interpretation of the integrated results.



## 2 TOPTIER PROJECT

### 2.1 Background

The sea environment is harsh and poses challenges and dangers to shipping. Safety does not only rely on seaworthy ships and properly declared, loaded and secured cargo. Safe operations require that relevant hazards are known, controlled and handled, or avoided if they can't be controlled. It relies on qualified, able and well-informed crew observing good seamanship, and shore-based personnel. The baseline principle is to aim for zero loss of containers at sea by meeting these requirements.

Incidents however do occur. Suggesting that either not all hazards are known; that they are not always adequately controlled; that they were not avoided; or that they could not be avoided.

IMO imposes safety baseline requirements around cargo stowage and securing that are implemented by its member flag- and port- states. The evolution in the industry however has exceeded the scope and usability of existing rules and guidelines. Operating practice around planning, loading and operation of modern container ships involves multiple stakeholders, software systems, roles and responsibilities. These are insufficiently addressed in current IMO rules that unrealistically hold the master singularly responsible for the proper stowage of containers. Harmonised functional and performance standards seem lacking and the resources to supervise, inspect and enforce compliance by flag state and member states fall short. Reducing container loss at sea in relation to actual incident numbers, requires review and improvement of the container transport process as it is today.

TopTier set out to identify the dominant root causes for container loss at sea and recommend improvements to tackle these, as well as review options to update regulatory frameworks in order to drive adoption of improvements into ongoing practice.

### 2.2 Goal

The objective of TopTier is to lower the probability of loss of containers at sea. TopTier's mission is to achieve this by reviewing and reporting on the relevant aspects of container transport by sea in appropriate fora such that:

- challenges and hazards at sea are identified and documented;
- improved options are identified to control or avoid these hazards in operation; and
- the regulatory framework is updated accordingly by bringing the results, conclusions, and recommendations of TopTier, to the attention of international regulatory bodies (e.g. IMO, ISO).

### 2.3 Consortium

TopTier addresses these objectives and mission together with 43 participants including national authorities, major carriers, class societies, insurance, lashing gear makers, system vendors, associations representing container line operators, container owners, cargo insurers and P&I clubs, and independent knowledge centres and universities as TUHH, TNO, and MARIN. This wide consortium of stakeholders was brought together to provide the required expertise to address the problem, and aim for leverage as needed for acceptance and subsequent required action.

Regretfully the consortium did not include principal terminal operators. Contacts with terminal operators were opened at the beginning and throughout the project but none joined in the actual project. That is considered as a loss, given the key role that terminals have in the ship-shore interface around the planning, loading and securing of modern container ships for sea worthiness.



Figure 2-1: Participants of the TopTier joint industry project

The project was set up as a Joint Industry Project (JIP) organised by MARIN. It offers a route to combine available expertise and carry out extensive and costly research sharing cost, efforts, findings and knowledge over multiple parties. All partners and sponsors (industry, authorities and research) were represented in a project steering group that allowed for strong involvement, cooperation and coordination of project progress.

## 2.4 Approach and schedule

The project duration was 3½ years. The TopTier JIP started April 2021. After extension with six months the project closing meeting was organised in November 2024. The project has been subdivided into three phases. It started with a review of current practice, including an incident review, crew survey and gap analysis. The most elaborate period was phase II in which the Working Groups carried out their research and investigations consisting of model tests, full scale measurements, numerical simulations etcetera. After this Investigations phase the findings were integrated and condensed to, where possible, concrete conclusions and recommendations. During this period a Project Steering Group meeting was organised every six months with all the project participants to inform about the progress and planned activities and elaborate on the way forward.

The TopTier JIP was organised into six working groups, each dedicated to a specific scope:

- |                  |   |
|------------------|---|
| Working Group 1. | Long term strength of lashings and containers |
| Working Group 2. | Stowage planning, loading and securing stage  |
| Working Group 3. | Extreme motions at sea                        |
| Working Group 4. | Cargo securing forces                         |
| Working Group 5. | Vessel operation                              |
| Working Group 6. | Regulatory aspects and standards              |

The working Groups were led by TUHH, MARIN, MTI, TNO and AMSA (Australia). Working group meetings were organised with participants that specifically registered for this working group.

### 3 THE PROBLEM OF CONTAINERS LOST AT SEA

#### 3.1 General

Approximately 250 million containers are transported by sea each year and a very small fraction of these containers is involved in accidents and is lost overboard. Containers lost at sea (CLAS) have an impact on the marine and coastal environment and on the safety of mariners at sea. Even though the percentage is small, the shipping industry is committed to protect the ship's crew, the environment, the cargo and the ship. There is also a concern by the public regarding incidents involving container losses

The challenge is to reduce the numbers of containers lost at sea to as close to zero as possible, thus reducing the hazards that cargo collapse incidents pose to crew on board, the environment, and other ships. That requires understanding the reasons behind occurring incidents, mitigate these for the future, thus aiming for a zero loss of containers.

Following paragraphs highlight the extent of incidents including references to the incident statistics. This is followed by an overview of which safety mechanism are in place, the room for improvement from seafarer perspective, the type of root causes that could trigger incidents, and a review of the relevance of the various root causes based on the statistics.

#### 3.2 Incident statistics

Incidents are reported to coastal authorities and ships in the vicinity. Details of cargo lost, usually remain between carriers and their insurers. Some incidents are investigated by maritime administration and involved port state. To date there is no mandatory or regulated centralised collection of the numbers of containers that are lost at sea and the circumstances or (provisional) root causes that were involved. Mandatory reporting of containers lost at sea will take effect global as of 1 January 2026. Pending this, TopTier collected information on incidents involving container loss from following sources:

1. The World Shipping Council (WSC) has since 2011 published annual reports with container losses based on data collected from its members. Those members represent more than 90% of worldwide container fleet owners/operators. The reports provide an overview of container losses during 2008 – 2023. The WSC data is generally accepted as being the best available representation of the annual losses. The average annual number of containers lost at sea over the entire period is 1482 containers in relation to an approximate number of 250 million containers currently transported annually. Reported losses by WSC members were lowest in recent years 2022 and 2023 with 661, and 221 containers lost respectively.
2. Data analytics that were referred to in the publication: “High waves, high claims”, by Gard<sup>1</sup>. This paper was based on aggregated findings from collected claims from the Gard portfolio. It addressed the probability of claim incidents involving cargo loss at sea, as function of ship size. Exposure to severe weather, and choices for operational weather thresholds were suggested as likely explanation. It was shown as fact that larger vessels have higher likelihood for incidents, while at the same time, the majority of incidents, occurred with smaller vessels. However the analytics did not include the total, or typical number of containers lost per individual cargo loss incident as function of ship size.

*“Analysing incident numbers relative to number of vessels in our portfolio provides valuable insights on claims frequency across different size segments, which can range from feeders (less than 3,000 TEU) to ultra-large container vessels (ULCVs) exceeding 15,000 TEU where the stack heights can exceed 10 high on deck. Despite a higher number of incidents on smaller vessels, there is a clear correlation between incident frequency (or likelihood) and vessel size, as depicted in the graph below. The 6-year average claims frequency for stack collapses on feeder vessels is 1%, whereas for ULCVs, it rises to 9%”*

<sup>1</sup> GARD Feb 2024 <https://www.gard.no/articles/high-waves-high-claims-new-study-on-container-losses/>

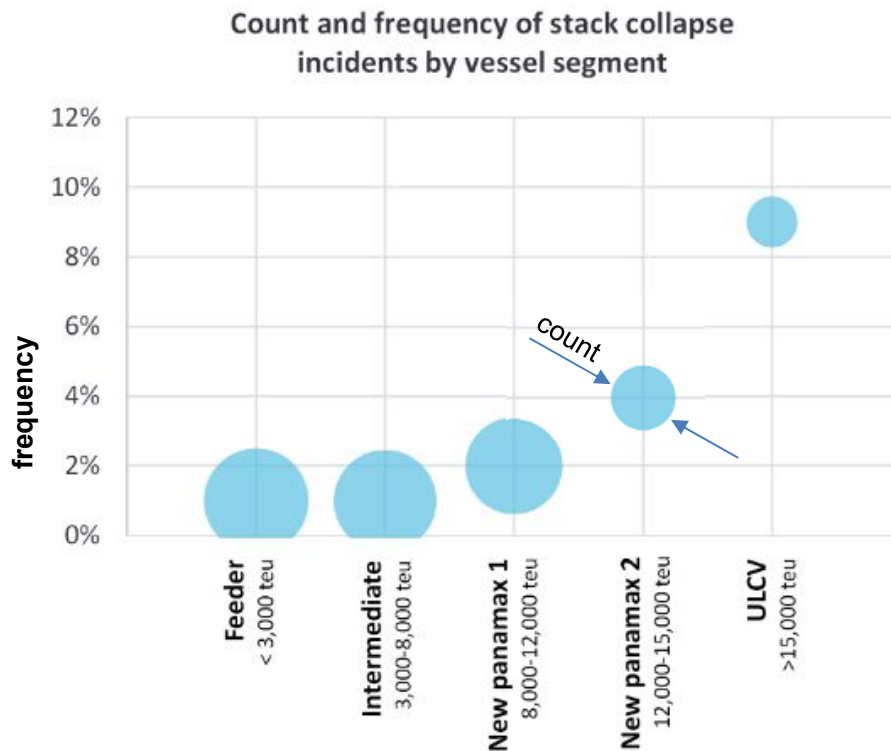


Figure 3-1: Incident count and frequency ref Gard February 2024. (Absolute counts not published)

3. An overview of references to individual incidents was established within the TopTier project, from press articles and formal investigation reports available in the public domain. This produced an overview of 44 identified incidents together representing a total of almost ten thousand containers lost over a period of 20 years (see Ref. [23]). The documentation in the public domain appeared to focus on the more severe incidents. Only few references were found to incident cases with smaller ships even though these should occur more often as indicated by insurance analytics. A large fraction of incident context and root causes is missing in the documentation collected from the public domain.

According to the WSC data for 2008-2023, on average 1482 containers are lost at sea per year. The approximate number of containers carried by sea each year is around 250.000.000. The percentage of losses compared to overall volume is small (0.0004%). The variation between good years and bad years ranges from few hundreds, to several thousand when big incidents occur.

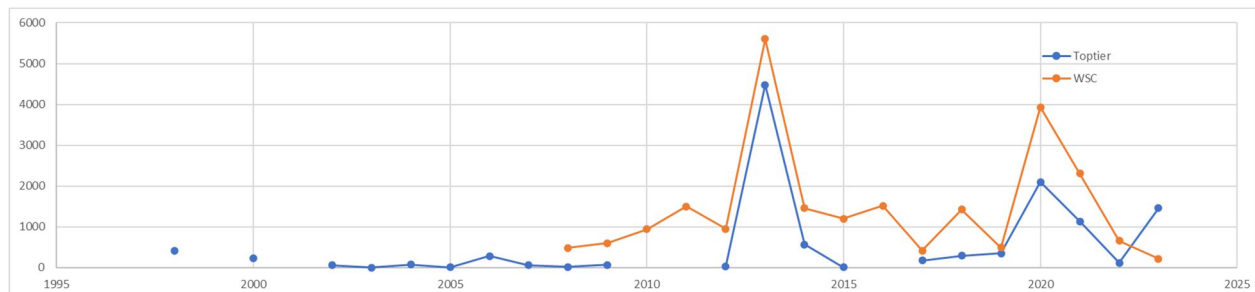


Figure 3-2: Comparison incident numbers WSC reports – TopTier review

Quantitative information relating frequency of incidents and scale of incidents to ship size and fleet size per size category is unavailable. Combining overall loss statistics from 1, the findings from 2, and the incident reviews from 3, suggests that:

- Only half of the average annual losses is explained by incidents reported in formal investigations and references available in public domain. These reports focus on high impact incidents. E.g. large

scale/big losses per incident, or with high consequence due to hazardous cargo, fire or environmental impact.

- The remaining half of the annual losses is then related to a larger quantity of small-scale incidents likely to occur on smaller ships, that are missing in public domain news and reports.

The combined losses from an unknown, but large number of undocumented, small-scale incidents have similar order of magnitude as the combined losses from large scale high visibility cases that are reported and documented in the public domain.

In the TopTier incident review (Ref. [23] and IMO INF paper Ref. [32]), 44 incidents were investigated and another 13 known incidents contained too little information to evaluate and were disregarded. From half of the incidents an official report was available from flag states, from the other ones, only information from public sources and the internet was used. In the evaluation the main uncertainties were missing information on transverse stability (48% of the incidents), missing speed (10% of the incidents) and uncertainties in time and position. Still the roll natural period was estimated as well as the wave height and wave encounter period from ECMWF ERA-5 wave hindcast data. Container loss and damage was taken from the incident report or from the internet and cross checked with photos.

The largest incidents (in terms of lost/damaged containers) happened on the Pacific and along the European coast. On the other hand most of the incidents happened close to the coast. The wave conditions ranged from only 2.5 m up to more than 12 m and was on average 5.3 m. Below table shows the classification of the incidents with the rows showing the type of damage and the columns showing the expected seakeeping behaviour based on the wave conditions.

Table 3-1: Classification of incidents in TopTier Incident Review

	Resonant roll	Parametric roll (stern)	Parametric roll (bow)	Head & bow quartering	Unknown	Total (%)
(Partial) stack collapse	7%	-	-	7%	5%	18%
Single (stern) bay collapse	9%	2%	2%	9%	11%	34%
Multiple stern bay collapse	5%	-	2%	-	2%	9%
Multiple bay collapse	7%	9%	7%	-	2%	25%
Unknown	2%	-	2%	5%	5%	14%
Total [%]	30%	11%	14%	20%	25%	100%

Figure 3-3: Percentage/overall incidents

	Resonant roll	Parametric roll (stern)	Parametric roll (bow)	Head & bow quartering	Unknown	Total (%)
(Partial) stack collapse	0%	-	-	0%	0%	1%
Single (stern) bay collapse	2%	2%	1%	4%	3%	11%
Multiple stern bay collapse	2%	-	1%	-	0%	4%
Multiple bay collapse	11%	41%	23%	-	6%	81%
Unknown	1%	-	0%	0%	2%	4%
Total [%]	16%	43%	26%	4%	11%	100%

Figure 3-4: Percentage/number of lost containers

The left matrix shows the percentage of incidents compared to the total number of incidents and the right matrix shows the percentage of damaged and lost containers compared to the total number of lost containers. It shows clearly that most incidents are most likely caused by large roll angles due to either resonant or parametric roll. The incidents in head and bow quartering seas denote the incidents in which large vertical accelerations might have happened, but maybe also green water loads, and high accelerations caused by slamming and springing. The remaining cases cannot be coupled to specific seakeeping behaviour due to lack of information. Most of the containers are lost or damaged when multiple bays collapse (81%) but in terms of number of incidents single stern bay collapses happen most frequently.

### 3.3 How is container stowage and securing “safe”

Container ships are designed with particular stowage arrangements that have specified maximum number of stowage positions or slots. They are outfitted with a securing arrangement comprising of lashing gear, fixed and loose, and lashing bridges on bigger ships. The securing arrangement has a specified maximum securing capacity in terms of overall stack weight that may be loaded into each row, and maximum specified safe working loads in terms of lashing and reaction forces that may occur at sea.

Stack weights and lashing forces in high tier stowage configurations can easily exceed maximum safe allowable loads without careful planning. Cargo arrangements are therefore planned to maximise cargo intake with the constraint that extreme forces under severe conditions will not exceed safe working loads.

The designated loading officer validates stowage plans for seaworthiness prior to and during loading and discharge operations. The checks are done using lashing software, based on a digital representation of the stowage configuration. Multiple stakeholders are involved. Loading operations are executed by a shoreside loading terminal in consultation with stowage planners of the carrier and the vessel. Shore teams or vessel crew fit the specified securing arrangement as documented in the ship's cargo securing manual, or as indicated by lashing software.

Safety thus relies on careful stowage planning, adequate performance of the lashing software that validates the plan, conformity between the validated stowage plan, and the actual stowage, and conformity between the securing arrangement as fitted on board, and what was considered in the validation.

Minimum safe standards for these aspects are imposed via the IMO SOLAS requirements that

- 1) the vessels stowage and lashing arrangement, relevant aspects around stowage planning, loading and maintenance are to be documented in a cargo securing manual (CSM) and be approved by the vessels administration.
- 2) The approved CSM must be on board, and cargo operations must be performed in accordance with it.

An overall review of current practice in container shipping is described in the “review of current practice” (Ref. [1]). Key aspects regarding cargo stowage and securing safety are reviewed in “Summary of incidents and gap analysis” (Ref. [32]). That report was submitted as Information paper to IMO. The highlighted aspects were the starting point for the scope of investigations that were carried out in TopTier phase II “technical investigations”.

### **3.4 Seafarer perspective**

The TopTier Joint Industry Project (JIP) survey carried out in Q4 2022 and Q1 2023 aimed to better understand the current decision-making processes on container ships, and collect direct feedback from crews on board with respect to the hazards for container loss at sea. The response was overwhelming both in quantity (with over 1500 responses) as well as in quality.

The survey responses clearly indicate a number of areas where crews see opportunities for improvement to reduce risk in the transport of containers, both when it comes to operations ‘Prior to departure’ and ‘During sailing’. For the complete overview and interpretation of the results see Ref. [2]. A condensed public overview of the 13 main points of attentions can also be found in the ‘Thank you note’ Ref. [26].

On the 16th of August 2022 TopTier Working Group 5 held a virtual meeting aimed at discussing and prioritising the 13 points of attention. A digital tool called QANDR was used to collect and visualise the opinions of the attendees. Based on the judgement of TopTier Working Group 5 most attention points from the crew survey are considered to have a high impact on container loss and are granted high priority to be picked up in the TopTier JIP. The prioritisation made by Working Group 5 can be found in Ref. [13] and more information on the follow up can be found in Section 4.6.

### 3.5 Root causes and their relevance

Root causes for container loss incidents were determined based on review of current practices, incident reviews, interviews with stakeholders, and crew questionnaires as circulated within the project. Multiple root causes were identified originating in various stages of the container transport operation as indicated in Figure 3-5.

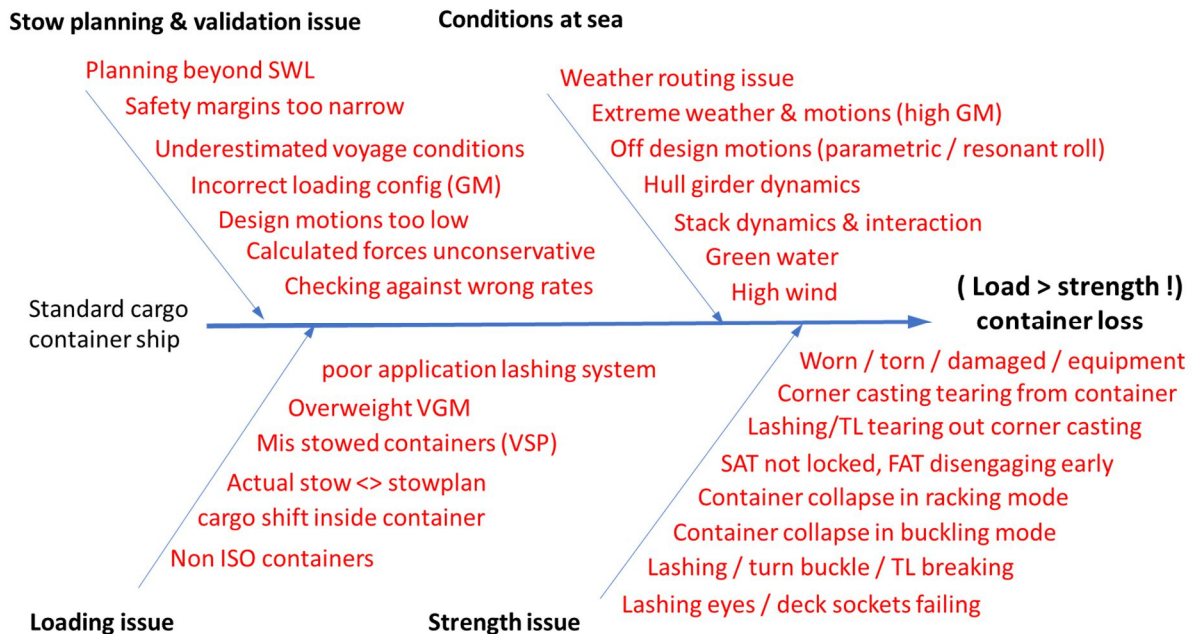


Figure 3-5: Root causes to container loss incidents

The overview highlights events that can trigger an incident. The right hand side refers to conditions and phenomena at sea that can raise excessive loads, or reduced strength of the securing arrangement. The left hand side refers to flaws in the preparation stage (planning and loading) resulting in stacks being planned too risky, or a stowage diverging from the agreed plan. Key aspects to be considered are the following:

- **Strength issues:** There are uncertainties in the strength of the stowage and securing arrangement that comprises vessel owned lashing gear and the containers that are stowed. One outlier (i.e. one container or lashing with poor strength) can cause a failure even at low loads.
- **Conditions at sea:** In transit conditions, the cargo arrangement is exposed to a range of loads and motions with a range of uncertainty that is depending on the environment in the sailing area, the stowage arrangement, and the vessel handling. Unforeseen loads can cause failures when they exceed strength limits.
- **Stow planning & validation issues:** Safe stowage plans rely on the ability to estimate realistic extreme securing forces in the voyage, and on leaving appropriate margin for the unpredictability of the sea and the complex dynamics that can occur in the stowage. Underestimation in the planning stage, can lead to failures in transit stage.
- **Loading issues:** Assessment of safe stowage is based on the digital representation of the stowage arrangement. The ships master cannot realistically inspect and ensure that the digital representation and the actual stowage are aligned. A loaded stowage arrangement that is not compliant with a validated stowage plan is potentially not a safe stowage.

The majority of containers lost at sea over recent years were related to incidents with excessive motions. Motions that exceed design limits, affect the entire stowage and can trigger gross scale cargo loss, ranging from dozens to thousands of containers per incident. These have highest impact and visibility. The root causes to these incidents were noted as weather conditions in excess of expectations, but in particular unexpected ship and cargo behaviour under normal sea state conditions. E.g. Excessive parametric and resonant roll, but also stack and multi row resonance. These incidents are very visible and widely covered in the news if they occur. They do however only add up to around half of the consolidated number of containers reported lost by WSC members. The other half appears to be not clearly documented in public press and open domain reports.

The majority of incidents in terms of ship specific events are of small scale. Because of high frequency of occurrence the overall contribution of smaller scale incidents is of equal significance as the “few” but large scale events caused by excessive motions. Adverse weather is a common factor in most incidents. Firm evidence is missing, but the main drivers for small scale incidents are believed to be uncertainties in the overall container transport process chain causing failure of a local weakest link at some point. An overview of the relevance of the various aspects is listed in Table 3-2.

**Table 3-2: Relevance of root causes related to container loss at sea**

keywords	description	Occurrence	Scale	Impact	Proven
<b>Off design ship motions, Parametric and resonant roll</b>	Hundreds to thousands of containers lost per incident, huge waste and impact at single incident location.	rare / any ship	huge	Extremely high	+++
Extreme weather, wind, waves, <b>beyond expectation or routing.</b>	The system is prepared for the expected worst conditions. Incidents are triggered when conditions are worse than expected.	occasional / any ship	huge	very high	+++
<b>misstowed</b> containers, or <b>underdeclared</b> VGM	Triggers small incidents, but likelihood relates to entire transport volume -> High probability of occurrence, adding up to large numbers / impact.	often / any ship	small	very high	+
Poor <b>condition</b> by wear and tear of lashing gear, or containers	Reports often relate Incidents to worn gear. Avoidability of wear and tear related incidents has negative public impact. Occurrence is frequent due to large nr of small vessels in operation that are also aging.	frequent / older ships	small/large	very high	++
Off design dynamic effects by hull girder, stack and <b>multi row resonant dynamics.</b>	Potential full bay losses involving order of hundred containers. But negative public exposure even with mld losses since the tell tale failure modes are picture perfect and keep circulating in the public domain.	occasional large ships, high tiers	large	high	++
Poor stowage / Cargo shifting inside container	Probability relates to entire transport volume and occurrence is often. Consequences usually limited to container content, but can damage and collapse stack	regular / any ship	small	high	+

## 4 TOPTIER RESEARCH

### 4.1 General

The project has been subdivided into six working groups, each dedicated to a specific bounded scope covering strength of lashings and containers, stowage planning and loading, ship motions, cargo securing loads, ship operations and regulatory aspects. These working groups contribute to the overall project goal with targets that are complementary. In the subsequent paragraphs for each working group, a condensed factual documentation of its baseline considerations, objective, scope and deliverables and main findings is provided.

### 4.2 Long term strength of lashings and containers

Strength and safety margins for lashings and containers was addressed in Working Group 1. The work was coordinated by Technical University of Hamburg. There was a small overlap with performance of inspection and maintenance regimes that was addressed in Working group 2 under coordination of MARIN. Key inputs were provided by project partners as follows:

- BIC and WSC for relevant standards, liaising to ISO TC104 working groups and highlighting known concerns.
- Container carriers providing container samples and lashing gear, and results of inhouse container inspections.
- Lashing gear manufacturers providing samples of lashing gear, and support in load case assessments.
- Class societies for comments to adopted approach in performance tests.
- AMSA feedback on lashing and container strength issues based on results of port state inspections.
- TT-club interfacing with port and terminal representatives for operational feedback and involvement from stevedores that were not part in the project.
- Results of a large scale corner casting survey performed by one of the project participants.

#### ***Baseline considerations***

The fundamental idea of standardised container shipping from strength perspective, is that cargo can be loaded up to a point determined by the strength of the ships outfitted cargo securing system. Validations of stowage plans for seaworthiness check that calculated loads for a proposed stowage don't exceed safe working loads under expected worst weather and motion conditions. Safety factors between safe working loads, and minimal break loads of the equipment provide a margin that accounts for uncertainty of actual break loads, and uncertainty in predicted / expected extreme conditions and loads. E.g. due to effects such as the unpredictability of weather and sea, and the complex behaviour of the cargo. If calculated loads are within the safe working limits, then probability of failure either by unexpected low strength, or by unexpected extreme motions, is considered acceptably low.

#### ***Objective***

The objective of Working Group 1 was to investigate the combined strength of containers and lashing gear.

#### ***Scope and deliverables***

The investigation included review of standards, experiments, and numerical simulations. Review of standards for generic design and test requirements; Experimental tests to determine material properties of various age equipment, effective strength of combinations of twist locks and corner fittings of various age; Numerical simulations to determine sensitivity to buckling of corner posts. The results are delivered in the following three reports:

- Mechanical tests of containers and material models (Ref. [10]).

- Experimental test of container castings and locks (Ref. [16]).
- Numerical Analysis of Container Strength (Ref. [15]).

### Findings

Review of standards:

Baseline strengths for new containers, and lashing equipment are defined in ISO standards (ISO-668, -1496, -1161, -3874, -17905). These are practically implemented by:

- Standardised containerships have stowage and lashing arrangements with minimum baseline performance via SOLAS requirement that CSM is approved by the Administration or by an authorised classification society. Class rules for lashing notations typically are based on ISO standards for lashing- and container- gear.
- Operational requirement that loaded containers are compliant with ISO standards when certified. (Certified ISO compliant containers, or Shipper Owned Containers that may not be certified)

Continued compliance to standards for containers in service is imposed via the Convention for Safe Containers or CSC. Many of the concepts in the ISO standards are re iterated. In addition however particular inspection/control requirements (PES/ACEP), and max allowable tolerances for corner casting apertures in excess of ISO standards are mentioned.

Continued compliance of lashings equipment to minimum performance levels is invoked by inspection / maintenance procedures as outlined in ISO standards (ISO-17905). Inspection and maintenance procedures have to be outlined in the CSM for approval and logged for PSC and class inspections.

Minimum break loads, proof loads and safe working loads according to ISO standards are listed in Table 4-1 . Stack collapse can be triggered by failure modes of container structure, lashing gear, or combined. Effective strength is determined by the first loaded component that is overloaded in a particular load case.

Table 4-1: Basic securing arrangement failure modes according to ISO standards

Basic failure modes	SWL kN	Proofload kN	MBL kN	ISO
<b>Container failure modes</b>				
Corner post compression - buckling	-	942	-	ISO-1496
Racking collapse - lateral loads	-	150	-	ISO-1496
Top & Bottom corner castings vertical restraints		300		ISO-1161 in review
Bottom corner castings longitudinal restraints		350		ISO-1161 in review
<b>Lashing failure modes</b>				
lashings-rod/eye tensile failure	245	375	490	ISO-3874
Twistlock tensile failure	250	375	500	ISO-3874
sockets deck, hatch covers, stanchions - tensile	245	375	490	ISO-3874
Twistlock shearing failure	210	315	420	ISO-3874
sockets deck, hatch covers, stanchions - shear	210	315	420	ISO-3874
<b>Combined / complex failure modes</b>				
CC tearing out container frame	CC mount to container not described			ISO-1161 / ISO 1496
Lashing hook pulling out CC fore/aft aperture	combined strength tests not specified			ISO-1161
Twistlock pulling out CC top/bottom aperture	combined strength tests not specified			ISO-1161/ ISO 3874
Container collapse by internal cargo shift	Relied upon max rate and CTU code			

Following is noted:

- Lashing gear has defined safe working loads (SWL) relating to proof loads and minimum break loads (MBL). Safe working loads are typically 50% of MBL and proof loads at 75% of MBL.
- ISO standards for containers as outlined in ISO-1496 and ISO-1161 require proof loads but do not list safety margins. Ref ISO-1496 par 5.1 General: *“As the effects of loads encountered under any dynamic operating condition should only approach, but not exceed, the effects of the corresponding test loads, it is implicit that the capabilities of containers indicated in Annex A and demonstrated by the test described in Clause 6 shall not be exceeded in any mode of operation”*
- Strength ratings for lashings / twist locks and the container corner castings they are attached to are different. E.g. Lashing gear can have specified minimum break load of 500 kN where containers only have 300 kN proof load.

An experimental / numerical scope of work addressed the strength of the integration of the container castings into the container frame, and the performance and strength of combination of aged twist locks and corner castings. Following was learned:

- Finite element calculations for a standard 20 ft container are performed in the linear elastic domain, linear buckling analysis
  - The container structure is based on available ISO CAD drawings (e.g. Found at [pacificmarine.net](http://pacificmarine.net) for post details). Under the assumption that the full-compressive proof load of 942 kN is only carried by the post cross-sections results in stresses of 240 MPa for the back post and 364 MPa for the front post. This estimate does not account for beneficial load distributions to other members, but also not for negative effects such as additional bending stresses.
  - Buckling of front posts are not found significant up to 100 kN load and beyond this value the model density becomes too high for reasonable computations.
  - High material stresses are expected in the welds and material around the corner castings under limit state loads in lashings and twist locks. This however appears to be triggered by improper welds and connections and it is indicated that those reduce the nominal strength significantly. Such stresses are exaggerated in the model below, but indicates those as vulnerable points in the linear elastic runs. Non-linear simulations confirm this with material data from the tested frame elements with a yield strength of 400 MPa (see Figure 4-1).

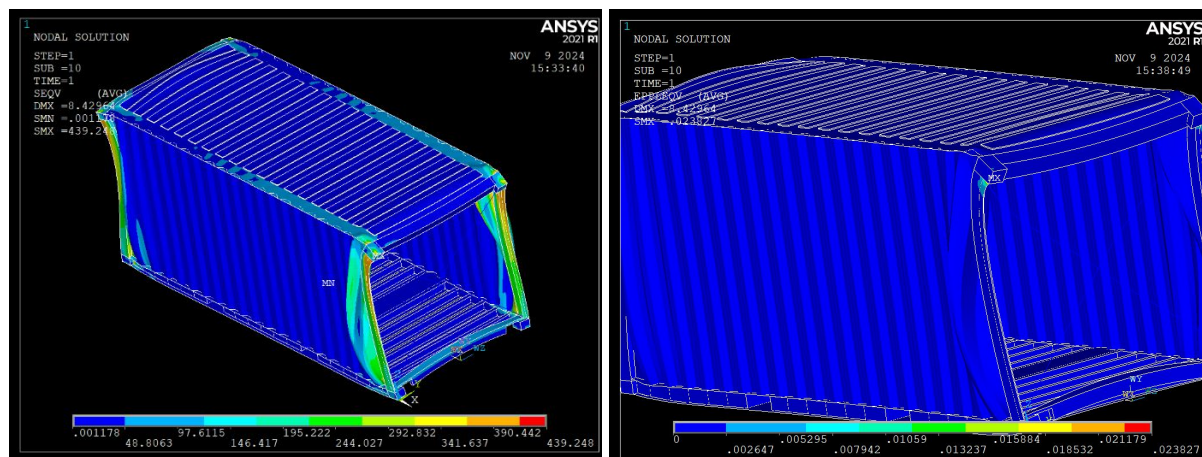


Figure 4-1: Von Mises stresses of non-linear simulations at 942 kN proof load at each corner (left) and plastic strain of the non-linear simulations highlighting the post-corner cast transitions as vulnerable element (right)

- Containers often show significant damages on the side walls and simulations including observed damages did not indicate an impact on the global strength, which is mainly carried by the posts. Non-linear simulation with an anticipated lateral pre-deformation (e.g. damage in operations) at one front post (see Figure 4-2, left) did not show a significant impact in the non-linear simulations. This is due to the load related deformation being in a different plane and the 40 mm deformation are still small compared to the length of the post. (see Figure 4-2, right). This pre-deformation is significantly larger than the previously compiled buckling cases.

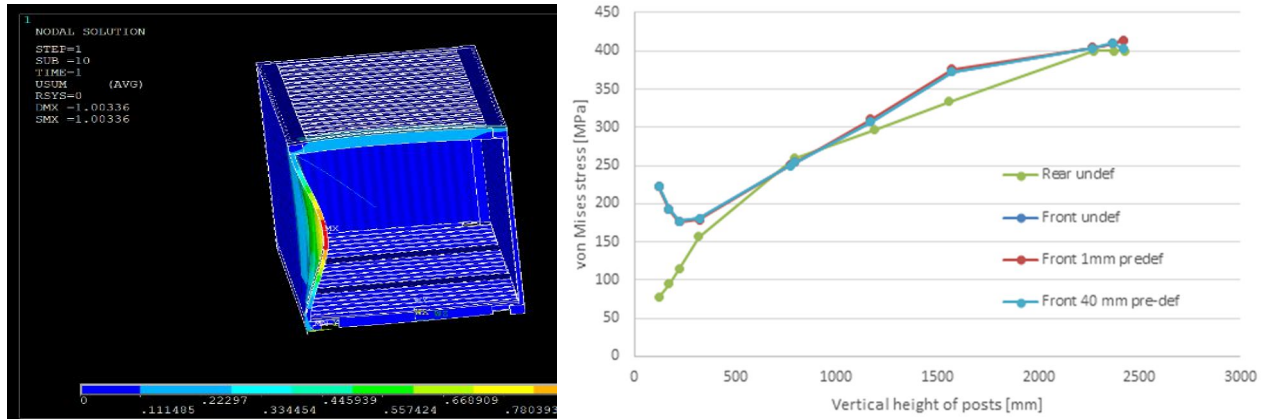


Figure 4-2: Pre-deformation of 1 mm (left) von Mises stress variations over the length of the posts for an un-deformed post and pre-deformations of 1 mm and 40 mm. The progression at the rear post without pre-deformation is included as reference (right)

- Based on the material tests it was found that the yield strength of the frame is around 400 MPa and Figure below shows the resulting deformations under the proof load.
- Specimen tests on material samples taken from container frames around the corner castings indicated that these containers experienced local yielding / plastic deformations near the corner castings.
- Cracks were found in the plate material and welds connecting corner castings to the container frame, where also the plastic strains in Figure 4-1 (right) are found.

Loading tests with a dedicated test bench (Figure 4-3) showed that:

- varying age semi-automatic twist locks and corner castings performed in line with break loads according to standards. The sample was too small to be significant but sample mean break load was 508 kN with standard deviation of 46,4 kN.
- Similar tests for full automatic twist locks (FAT) showed that results are sensitive to geometric properties of the corner castings and the alignment as imposed by the test rig. Especially small movements/sliding of corner castings in the direction of the racking force resulted in results not fulfilling the standards. These movements were below 2 millimetres and resulted in a lifting force of 260 kN (standard: 275 kN) for three specimens. A more rigid connection hindering this movement resulted in fulfilled test for two additional tested specimens (317 kN). Heavy use fully automatic twist locks showed a much better loading capacity (444 kN; 1 sample) but revealed the same issue (265 kN with movements; 1 sample).

Standards for functional and performance testing as outlined in ISO codes, refer to equipment in new state. Aperture size in new condition is required to be within a range of 63.5 and 65 mm. CSC inspection requirements for equipment in operation allow max opening size of 66 mm. A large container survey of corner casting apertures in operation performed by a major carrier, indicated (25.2+0.6)% of overall samples exceeding 65 mm. A percentage of 0.6% exceeded 67.5 mm (refer also to par 4.3).

The negative impact of 2 mm lateral motions on tested FAT holding force in combination with the aperture opening statistics from the survey indicate that a percentage of the equipment will have max holding forces well below the specified tested break load, but in range of the specified safe working load.



Figure 4-3: Test bench corner casting - Twist lock samples

### 4.3 Stowage planning, loading and securing

Evaluation of the ship shore interface was done by TopTier Working Group 2. Work was coordinated by MARIN and supported by TopTier participants. External expertise was involved from independent surveyors, loading terminal representatives, Royal Institute of Naval Architects, and specialists on lashing systems that contributed via workshop discussion and follow up afterwards.

#### **Baseline considerations**

Seaworthiness has to be ensured before a ships puts out to sea. That includes proper loading and securing to avoid cargo shift, stack collapse or cargo loss.

#### **Objectives**

The objective in Working Group 2 was to identify and investigate challenges and complications with regards to safe cargo stowage and securing that occur in the ship-shore interface when the vessel calls into a loading port.

#### **Scope and deliverables**

Following aspects were addressed:

- Review of safe stowage procedures and standards.
- Crew questionnaire on loading procedures before departure.
- Evaluation of VGM reliability.
- Stowage surveys across four ships to identify miss-stows.

- Evaluation of impact by overweight VGM and mis stows on expected loads.
- Reliability of container corner casting aperture dimensions.
- TopTier workshop addressing feasibility of oversight over loading progress, inspection and maintenance of lashing gear.

Findings are documented in:

- Report 33039-12-PaS Container stowage planning & loading, MARIN. (Ref. [20])
- Mis-stowed containers on four large container ships, Taylor Marine, ref 4247/HFW/HR. (Ref. [4])
- Application of a MCS approach to assess safety levels in container stacks, GBMS, ref GBMS 2023-003. (Ref. [7])
- Workshop summary - shore – ship interface – Rotterdam - 2023-05 (Ref. [6])

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### Main Findings

Multiple stakeholders cooperate in cargo planning, loading and securing of a container ship.

Shipper	-> Providing cargo information
Carrier	-> Container loading list to be shipped
Vessel	-> Up to date arriving condition with available slots after discharge
Central planning	-> Make concept stowage plan. Block / slot assignment for optimized long term vessel utilisation
Terminal planning	-> Make prelim stowage plan. Individual containers assigned to concept slots for optimized terminal ops
Crew / Carrier	-> Validate prelim stowage plan for seaworthiness in conditions expected in the voyage
Terminal	-> Execute loading operations. According to the stowplan, or after agreement to deviate
Stevedores	-> Fit the securing arrangement
Crew	-> Oversee loading and securing operations
Terminal	-> Submit final stowage plan - as loaded - to vessel team prior to departure
Software developers	-> Software and data used in the "digital cargo eco system"

- Roles and responsibilities of individual stakeholders are not typically assigned by a formal chain of responsibility. Loading operations are performed under responsibility of the master.
- Safe stowage on container ships is determined by not loading cargo beyond specified safe loading limits of the vessels cargo securing arrangement. This is checked by validating preliminary stowage plans that are exchanged in UN/EDIFACT BAPLIE format.
- Classic stowage validation against approved weight patterns in the CSM has become unpractical. A new approach is based on calculated "utilisation factors" that are the ratio of expected forces versus allowable forces.  $UF = \text{expected force} / \text{allowable force}$ .
- Lashing software integrates calculation algorithms, and interfaces to shore & crew. Utilisation factors are calculated for all lashings, twist locks, container posts, racking loads and permissible stack weights. The maximum value represents the vessels' overall utilisation factor. 100% references the maximum condition that is considered "safe allowable".
- Safety is at risk when conditions at sea exceed what was evaluated in calculations:
  - Actual stowage differs from the validated stowage plan. (Miss stows or overweight VGM).
  - The strength of the securing arrangement is less than assumed.
  - Conditions at sea are worse than expected -> Addressed in Working Groups 3,4 and 5.
  - Calculated utilisation factors are too unconservative -> Addressed in Working Groups 3 and 4.

- An Australian survey was made available comprising 1580 containers weighting from 2.5 to 33.7 t, with average declared VGM of 24.4 t.
  - Mean value of all measured weights was 25.0 t. An average overweight of 2.3%.
  - Maximum observed difference was 6.1 t above declared VGM i.e. 25% overweight.
  - Worst outliers for containers in low weight categories (likely to end up higher in stacks)
    - 5 t weights : +1 t
    - 10 t weights + 3.5 t
  - Over weights of 3 and 4 t occur relatively frequent in 20 t range. That may be due to VGM being declared without tare container weight.
- Independent surveys were performed by Taylor Marine to test for mis stows. Tests were done on four ships during five surveys. Four surveys while discharging inbound cargo from Far East. One outbound survey was done prior to departure after loading in NW Europe. Inspections covered 30 bays in total, i.e. approximately six bays per inspection. The inspected bays were preselected to avoid stacks with empties. Findings were shared with vessel owners but were reported anonymised to the group. Key findings:
  - Significant numbers of mis stowed containers were detected.
  - Amount of mis stows per inspected cargo bay varied from 0 to 92%.
  - Average amount of mis stowed laden deck containers per ship was 10%.
- Carriers and masters noted serious concerns about discrepancies between stowage plans and actual loaded stowage on deck. It was reported however as well that maximum allowable stack utilisations were not exceeded after updating the original stowage plans with the mismatched positions.
- Potential impact of uncertainty in VGM and stowage positions was evaluated numerically by GBMS. A Monte Carlo evaluation was done with 10.000 variations of VGM and stowage positions. The distributions for VGM and stowage position uncertainty were obtained from surveys of VGM weight by AMSA in a Brisbane terminal, and the results of the stowage position survey by Taylor Marine. Evaluations were done for a 7-tier and an 11-tier stowage at 80 and 99% utilisation factors. Findings indicate:
  - Uncertainty in either container weight or in stowage positions increase the probability that design loads are exceeded. Negative impact is strongest when both effects are combined.
  - The impact relies on the stowage configuration in combination with ship type and external forces induced by the environment.
  - Corner post compression results were found most sensitive for the selected cases. Lashing and twist lock utilisations were around 60% and less.
  - The 7-tier case loaded to 80% utilisation, was found to exceed beyond 100% SWL in 17.5% of the cases, and beyond 120% SWL in 3.7% of the cases.
  - The 11-tier case at 80% utilisation was found to exceed beyond 100% SWL in 3.2% of the cases, but never beyond 120% SWL.
- Uncertainties as observed in the weight and stowage surveys can increase loads by 20% in 17.5% of cases for a 7-tier configuration and in 3% of cases for the 11-tier configuration.
- A topic that was listed but not researched is the handling of stowage bins for twist locks in lashing calculations.
- Incident reports and crew questionnaires highlight concerns about condition of containers, and ships' lashing gear.
  - Inspection and maintenance for ships' lashing equipment is imposed via ISO 17905. Inspection and maintenance guidelines are documented in the ships CSM. Maintenance logs have to be kept, but the condition of lashing gear is not commonly logged.

- Inspection and maintenance for containers over time is imposed via the IMO Convention for Safe Containers (CSC) requiring periodic container specific inspections (PES), or continuous container fleet inspections (ACEP). The majority of the container fleet is inspected under ACEP regimes.
- National administrations do limited oversight over ACEP regimes. Concern about ACEP inspections is raised successively to IMO CCC.
- ISO standard prescribes new corner castings apertures to be sized between 63.5 and 65 mm. The CSC convention lists 66 mm as the allowable limit for equipment in operation. A dedicated survey of 532 container corner castings as performed by a container carrier **Error! Reference source not found.**, highlighted 25.8% the tested sample to be outside of new build tolerances, and 0.6% even exceeding 67.5 mm. Aggregated results are shown in Table 4-2. **Error! Reference source not found.**

Table 4-2: Aggregated results corner casting dimension survey

Dimension readings	$X \leq 63.5$	$63.5 < x \leq 65$	$65 < x \leq 67.5$	$67.5 < x$	Total
Number	24	371	134	3	532
Percentage	4.5%	69.7%	25.2%	0.6%	100%

- There is concern on the performance of lashing arrangements because of age, wear and tear of lashing gear, and application of less stringent lashing patterns for shorter trips. Time pressure on ships crews during port calls is high, time between ports is short on coastal routes. Limited time is left for inspection and maintenance. Fatigue of crews is a problem. Resulting in hazardous working conditions, and potentially flawed lashing arrangements.
- Limited options exist to check equipment. There is a need for objective qualification standards of permissible gear. Some carriers have inhouse standards on inspections and maintaining condition logs for (fixed) lashing gear in order to facilitate scheduled maintenance or replacement.
- Lashing gear is difficult to inspect. Lashing bridges are many and high, time for inspections in port is short. Difficulty to inspect gear that is in use. Fixed lashing gear as deck sockets, but also twist locks that are handled by shore staff, can be inaccessible in the stowage, or inaccessible in stowage bins.
- Introduction of harmonised condition standards for lashing gear, and logging of condition status reports over time could enhance oversight and induce improved reliability of ships lashing gear condition.

### **Workshop with terminals and experts from RINA and ISO**

Terminal stakeholders did not participate in the TopTier project which imposed limitations on the extent of the discussion, consideration of perspectives and potential improvements. In order to overcome that terminal operators and lashing experts from RINA and ISO were invited for a workshop discussion with TopTier stakeholders. The workshop focused on uncertainties in the planning, loading and securing stage as identified in the shore-ship interface, possible improvements and the roles and potential roles for terminals.



Workshop conclusions with respect to stowage planning and loading:

- It is crucial for safety that the vessel knows actual stow configuration, and validates this for compliance with allowable criteria.
- It is unanimously agreed to be unrealistic that crew can check and control loading operations for compliance with stow plan. They have to rely on the terminal even though the terminal is not formally responsible for this.
- Reliability of declared weights has improved since the introduction of VGM, but question marks remain. Declared (VGM) weights are not systematically checked or enforced. Actual “as loaded” container positions are not checked or enforced. Compliance is based on trust. Deviations can pass without notice.
- Both carriers and terminals recognise concerns. Inaccurate stow plans cause problems for safety at sea, as well in efficient handling incoming cargo at discharge terminals.
- There is a need to ensure that the final stowage (or BAPLIE) plan adequately represents the stowage of containers on the ship and, further, that it is validated by appropriate means to be a safe arrangement prior to departure
- Deviations from the preliminary stow plan are unavoidable due to complications in the loading process that are normal in terminal operation. The key issue however is that these deviations should be communicated from the loading area to the terminal planners and the vessel team, such that the final and reliable stow plan can be (re)validated for seaworthiness prior to departure.

Workshop findings on inspections for lashing gear and container condition:

- Terminals have increasing concern about the condition of lashing gear. For older ships that was the case already. Gear on board new ULCS fleet is believed to deteriorate in five years due to limited inspection and maintenance.
- It is considered unrealistic that ship crews can effectively maintain their equipment. The numbers are too high, and cost of labour exceeds value of gear.
- Focus may have to shift to tracing of lashing gear conditions (loose and fixed) in order to notify for timely batch replacement. Replacement of integral batches is more efficient than inspection and maintenance of older.
- Terminals offer inspection and maintenance services for lashing gear already. Terminals also perform inspections of calling vessels to ensure their stevedores safe working environment. Including accessibility, fall protection, and lashing gear. Information is for internal use & bilateral contacts with carrier and lashing gear manufacturers if needed.
- Clearly damaged / worn containers are picked out in day to day handling ops by the depots of container owners, by packing stations, and terminals. Local damages that reduce securing strength such as corner casting damages, aperture deviations, indentations and cracking around the corners are only noted by specific inspection and may be missed in less strict inspection regimes.

Further and open discussion is needed between carriers, terminals and authorities to:

- Discuss the roles that terminals could play for vessel safety, alongside the existing drivers and KPIs between carriers and terminals around efficient loading.
- Discuss potential challenges around a requirement to maintain inspection status report logs over time for lashing gear and containers in order to facilitate scheduled condition based inspections and maintenance. E.g. Who, what and how to inspect, where to maintain logs as in central accessible data base, how to relate to existing assignment of roles as outlined in CSC.

The concern over the condition of lashing gear and containers is clear, but the actual impact on operational safety is not quantified due to the limited information that is available. Further efforts are needed to acquire that information and quantify the impact on operational safety.

#### **4.4 Extreme motions at sea**

Working Group 3 addressed extreme motions at sea. Both with respect to design extremes as considered in stowage planning stage (in-design), as well as how to avoid worst possible motions that are considered off design. Work was executed in cooperation with Working Group 5 on vessel handling and crew feedback, and with inputs from carriers, and class societies.

##### ***Baseline considerations***

In-design motions denote the worst expected conditions in the voyage, taking into account vessel handling according to good seamanship into account (e.g. heavy weather avoidance). Off-design motions denote, possible severe conditions that might occur in the voyage but that are considered to be avoided by good seamanship, like (but not restricted to) parametric roll, resonant roll, loss of stability, excessive pounding and springing and dead ship condition.

##### ***Objective***

Stay in-design and avoid off-design.

### Scope and deliverables

The scope of work and deliverables consisted of:

- Summary and review of container loss incidents (see Section 3.2, Ref. [23] and Ref. [32]).
- Model tests, to identify sensitivity of two different sized container vessels (10 kTEU and 15 kTEU) to parametric and resonant roll under different wave conditions, speeds and headings (see Ref. [8] and Ref. [9]).
- Release of a notice to mariners to raise awareness of parametric roll hazards in following seas (see Ref. [25]).
- Development of guidance tools to assist with assessment of extreme roll hazards.
- Simulations to evaluate the ability to avoid heavy weather, and predictability of parametric roll (see Ref. [19]).
- On board measurements, to identify operation motion characteristics in terms of rigid body motions, hull flexibility and these in relation to crew perception on comfort and the load imposed onto the cargo (see Ref. [15]).

### Main findings, Stay in-design

The vessel crew will handle the vessel to stay within the design parameters, according to good seamanship principles using their experience, especially their perception of the vessels behaviour. The findings of the on board measurements indicate that crews perceive substantial impact of motion conditions on comfort and cargo loads at moderate measured acceleration levels. For the 24 kTEU vessel the results are shown in Figure 4-4.

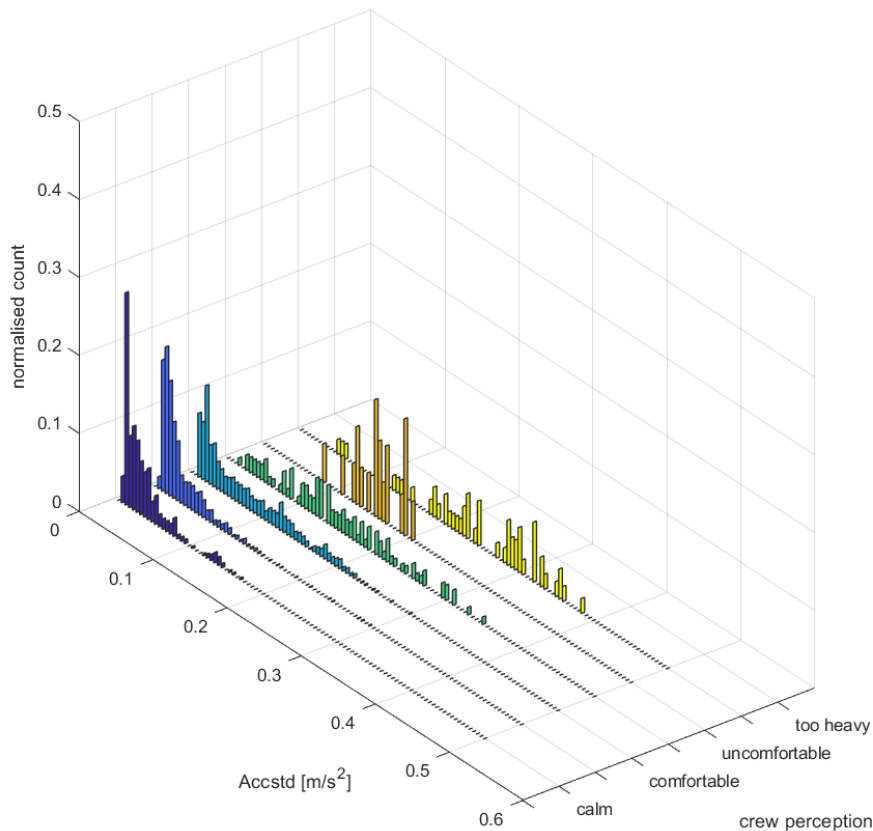


Figure 4-4: Crew perception vs measured accelerations (24 kTEU)

Measured acceleration levels with standard deviations of  $0.4 \text{ m/s}^2$  are rated as uncomfortable tending towards too heavy. That corresponds to maximum peak accelerations of around  $1.6 \text{ m/s}^2$  and corresponding effective gravity angles at the inclinometer just under 10 degrees. This suggests that ship crews will start to consider motion mitigating actions well within the design envelope considered in stowage planning calculations. Typically by speed or heading changes to minimise effects of forced, resonant or parametric roll. Highest motions were measured on the 14 kTEU vessel operating between Asia and America.

On board measurements further indicate that the perceived impact of vessel motion behaviour includes the effect of both rigid body motions and the effect of hull girder flexible deformation. Measured accelerations at the wheelhouse are generally dominated by roll related effects. Some cases however were flagged as uncomfortable / heavy loads that had mild motions, but strong contributions by hull girder vibrations. These vibrations consist of vertical and lateral bending, and torsion along the length of the hull. The typical periods of these “vibrations” are in range of 2 to 3 seconds. These are reported as uncomfortable to crew when moving around, and also induce dynamic response in the cargo stowage.

The overview of on board measurements also highlights the variability of the vessel’s loading conditions over time, and the impact that has on the natural roll period, and consequently, on the sensitivity to encountered wave conditions. An overview of the roll natural period obtained from motion measurements, and its correlation with GM as logged by the crews on board is shown in Figure 4-5.

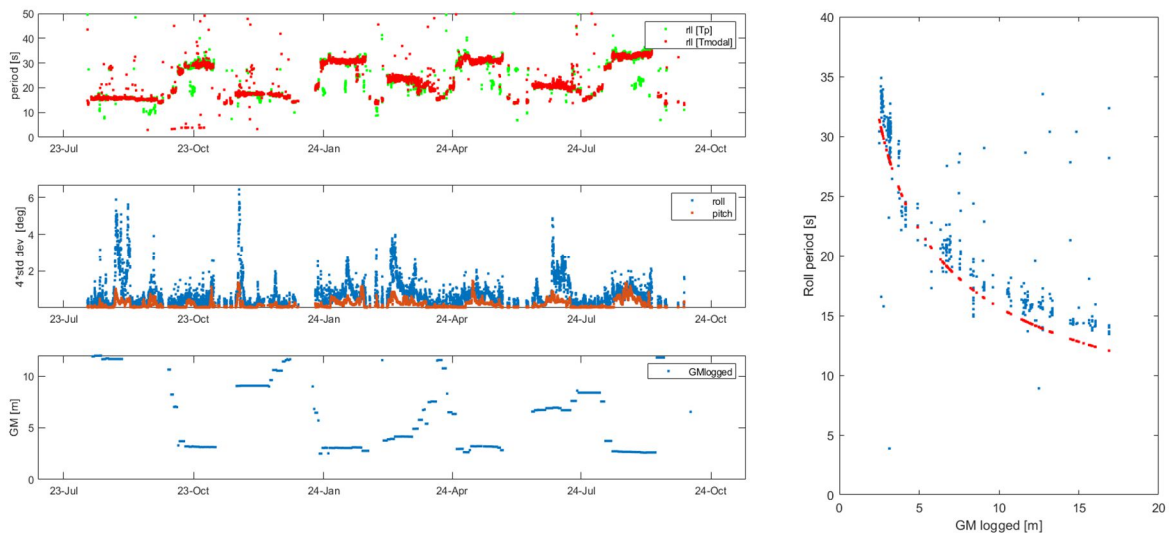


Figure 4-5: Roll natural periods from measured motions

The variability of both GM and the natural roll period, hence also the seakeeping character of the vessel in changing loading conditions is clear.

A reliable prediction of the roll period prior to departure is crucial for stowage planning, voyage preparation and vessel handling at sea. It is the starting point for the extreme motions that feed into the class approved operational solvers that calculate and validate maximum forces in the stowage against safe working loads. (see section 4.5). From Grin, 2024 (Ref. [29]) it is shown that present prediction methods for the roll natural period show large spreading and for instance the fully empirical method recommended by IMO is unsuitable for large container vessels (see Figure 4-6). Direct calculation of the roll inertia is recommended and is possible as all information is available from the loading computer and stowage plan. The second-best option is to apply a physics-based method that is not only relying on the beam of the vessel. Fully empirical methods are not recommended.

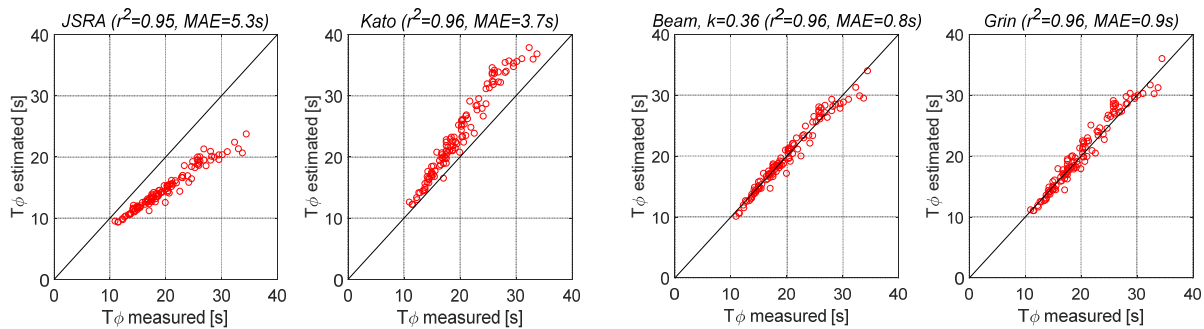


Figure 4-6: Differences in natural period prediction methods for a 9200 TEU container vessel (Accuracy improving from left to right)

Approaches to calculate worst motion conditions in a voyage, as implemented in seven different class rule methodologies were compared for a 10 and 15 kTEU reference vessel. Because of the amount of calculations and the extensive input, the calculations aren't done manually but are typically implemented in class provided or class approved software. The findings show that there is variation in the followed approaches and hence in the calculated design extreme motions. It is not straight forward to interpret and compare voyage specific design motions across different class approaches. A comparison requires the combined consideration of expected design motions + calculated loads along with the class specific criteria and correction factors on the strength side that define maximum allowed safe loads. Differences in intermediate results for motions and loads do not imply that calculated utilisation relative to the maximum safe allowable loads are incorrect (see also Section 4.5).

But since ships' safety relies on vessel handling, the crew must be aware and clearly understand the design conditions and motions that were considered in stowage calculations. Harmonisation of the definition and calculation of voyage extreme conditions and motions as used for the operational solvers would be a logical starting point.

In design motions could be regarded as the linear rigid body ship motions that would occur in the worst conditions to be expected in the voyage based on experience, under the assumption that ships' crew avoids occurrence of excessive non-linear phenomena as parametric roll and severe pounding. The in design motions can be reliably calculated, or be approximated with empirical formula. However, there are a number of uncertainties that include the definition of the worst expected sea state (e.g. considering effect of weather routing), the feasibility to avoid excessive non-linear roll and the accuracy of inputs as roll inertia and roll damping.

It is recommended to develop guidelines to ensure that the crew is aware of these sensitivities. For instance, by informing the crew up to which wave height it is very unlikely that the design motions will be exceeded. Or by asking the crew to cross-check actual roll natural period with the assumed one for the operational solvers.

### Main findings, Avoid off-design

Parametric and resonant roll were identified as root cause of many of the incidents (see Section 3.2, Ref. [23] and Ref. [32]), hence it was decided in the early stages of the project to release a notice2mariners (Ref. [25]) together with a roll risk estimator Excel sheet. Both aim at assisting the crew by indicating speed-heading combinations to be avoided in order to prevent parametric roll and resonant roll. They are validated with the seakeeping model tests done for the 10 and 15 kTEU vessel.

The model tests showed that parametric roll could occur in a wider range of wave conditions then generally assumed. Parametric roll was for instance found in almost beam seas (75 deg heading) and in almost following seas in only 2 m significant wave height (for further details see Ref. [8] and Ref. [9]).

It is recommended to not only provide operational guidance for parametric and resonant roll but also for other off-design behaviour which could result in container loss. Low fidelity approaches are often possible and valuable but might be (and should be) over conservative. For parametric roll it was shown that high fidelity approaches with 6DOF non-linear time domain tools require expert users and calibration with model tests (see Ref. [34]). Further guidelines are recommended to ensure reliable operational guidance. For this purpose it is recommended to make (part of) the model test results publicly available.

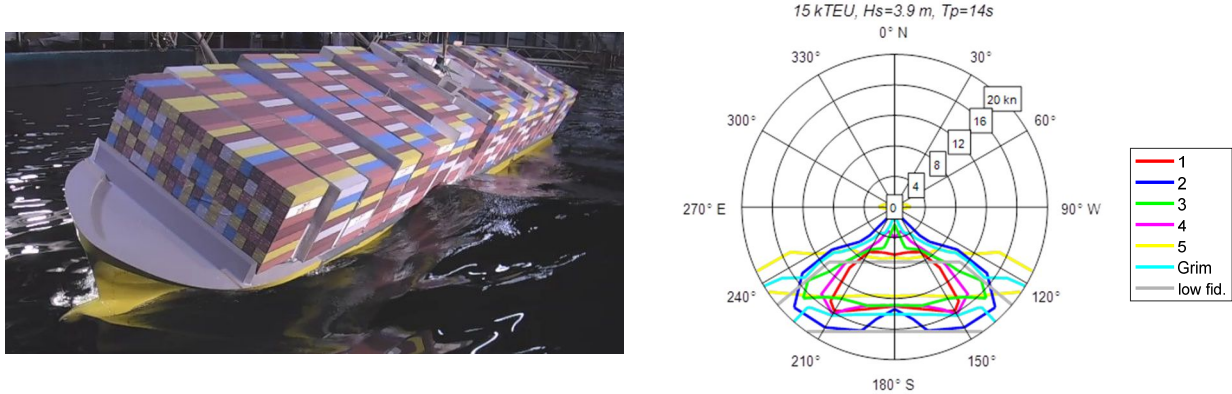


Figure 4-7: Example of 33 deg parametric roll in 7 m waves of 15 kTEU vessel (left) and example of variation in seakeeping tools that predict parametric roll larger than 15 deg (right)

#### 4.5 Cargo securing forces

Working Group 4 of TopTier focuses on the load calculations of ULCV cargo securing arrangements as performed by the operational solvers of different classification societies. The work was performed in cooperation between NYK-MTI, TNO, MARIN, the classification societies in the project, and GBMS.

##### Baseline considerations

Baseline considerations and context:

- Securing forces are the result of the behaviour and deformation of a container stack arrangement under external loads by wind, waves and inertial loads induced by cargo mass, in combination with earth gravity and ship motions.
- The forces in the containers and lashing equipment are not only affected by external loads, but also by uncertain operational factors such as lashing pretension, twist lock gap tolerances, container and lashing bridge stiffness, and the integrity of the container and equipment.
- Operational solvers are used in the design stage for appraisal of allowable stowage patterns for conventional CSMs, and they are integrated in present lashing- and stowage planning- software, that is widely used in stowage planning and loading of containerships.
- Operational solvers evaluate a simplified representation of reality in order to be fast, efficient and provide crews on board with a concise practical output (the utilisation factor). Class developed and tuned these solvers using a mix of high fidelity calculations, experience and feedback from practice over time.
- Industry stakeholders raised concerns about variation between the methodologies used in lashing software according to different classification society rules. Calling for a level playing field for safe stowage and securing requirements.

**Objective**

The objectives of Working Group 4 are listed as follows:

- Evaluate the behaviour of loosely stacked high tier cargo experimentally and verify the ability of high-fidelity physics-based tools to reproduce this behaviour to confirm that the basic physics are properly understood.
- Compare operational calculation methods (operational solvers) and assess scatter in container stack and securing loads as obtained according to the cargo securing rules and guidelines of different class societies.
- Identify key factors driving uncertainty in operational solver results and recommend improvements.

**Scope and deliverables**

To achieve the objectives of Working Group 4, four steps were taken:

1. Model scale experiments have been carried out at the MCS test facility in Yokohama, Japan on a scale 1:6 with 11-tier container stack at various loading conditions, twist lock gaps and excitation levels to provide reference data for a high tier, externally lashed stack with realistic scaled properties under static, regular dynamic, and resonant dynamic motion conditions (Ref. [12]).
2. Comparison of the model scale container stack experiment with numerical high-fidelity simulations performed by four participating classification societies (Ref. [11]).
3. Comparison of operational calculation methods (operational solvers) of seven operational solver codes providing accelerations and overall utilisation factors for six stacks on a 15 kTEU container ship at GM of 1.3 and 3.5 m (Ref. [15]).
4. Perform full scale container stiffness experiments to determine the racking and torsional stiffness of a 40 ft High Cube and 20ft ISO container with both doors closed and one door open (Ref. [21]).

**Main findings - Model scale and container stiffness experiments and analysis**

The main findings of the model scale experiment are:

- Overall securing forces are dominated by the inertial loads of rigid body mode displacement by rolling, and the container weight distribution across the height of the stacks.
  - Non linear container stack dynamics, uplifting and snapping, increased lashing loads by 23% under the worst tested conditions.
  - Quasi static contributions of the increased lateral displacements in higher tiers by uplifting and racking were found small in comparison to classic rigid body motions as induced by roll. (~100 mm vs 1400 mm -> 7% at roll angles of 15 degrees).
- The load sharing of cargo securing forces across multiple lashings and containers is highly nonlinear due to effects by container uplifting, different racking stiffness at fore and aft end of the container, the initial pretension in lashings and the tension only character of lashings.
- Highest loads occur in the upper lashings at rigid closed end side and corresponding corner castings. In the model test the upper lashings absorb up to a factor 4-5 higher loads than the lower lashings and 2 times more than the loads on the door end side.
- The flexibility of the door end side has a beneficial effect on load sharing between lashings at the door end side. The rigid closed end side has a negative effect on load sharing and results in the top lashing carrying most of the load.
- Resonant stack response to lateral accelerations with short periods (E.g. due to global hull horizontal bending or global hull torsional vibration) was found to induce similar lashing forces to large non-resonant heel angles. The high loads and frequency of occurrence can potentially cause failure or low cycle fatigue damage to lashings and corner castings.

- Resonant response of single row stacks was found to occur across a range of frequencies rather than at a fixed natural frequency. That is caused by nonlinear effects of uplifting as allowed by twist lock gap tolerance. It can be triggered by frequency lock-in following an initial high response event. The resonant frequency range is close to hull girder natural frequencies for torsion and horizontal bending.

In order to verify whether high-fidelity analyses can capture the relevant physics of nonlinear high-tier container stack behaviour, the results of the model scale experiments have been compared to numerical high-fidelity simulations performed by four participating classification societies. Different modelling approaches have been applied ranging from detailed sub-structured 3D meshes to beam models. All selected methods are based on the Finite Element method and applied an implicit solver to capture the non-linear behaviour. Figure 4-8 shows the comparison for the highest lashing forces observed in the experiment at the close end of the container, as an example of the comparison that was performed.

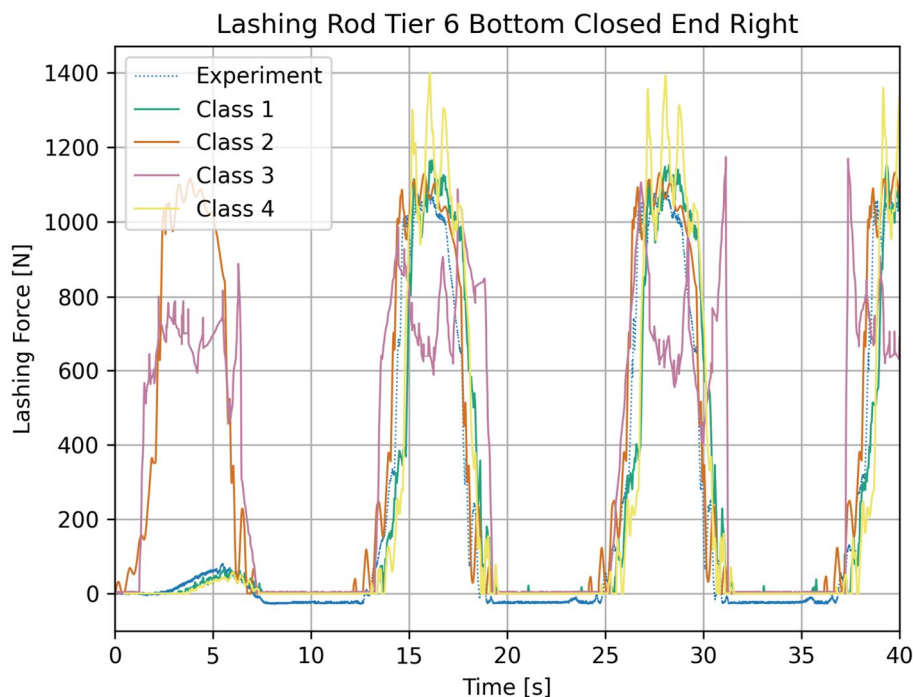


Figure 4-8: Bottom Tier 6 Closed end lashing rod (right)

The following key observations were made:

- The different high-fidelity codes and methods can predict non-linear stack physics including motions and forces.
- Comparing the different applied codes and methods reveal similar results with the expected scatter in this type of comparison studies.
- The container stack responses are predicted in the same order of magnitude in terms of overall motions, periods and forces.
- The effect of difference in racking and torsional stiffness of the container at the open and closed ends is observed and needs to be accounted for in calculating lashing forces.
- The effect of uplifting has a strong effect on lashing loads and needs to be accounted for in calculating lashing forces.

The comparison of model container stack experiments and high-fidelity simulations show that these codes are capable of simulating non-linear container stack dynamic behaviour including non-linearities, i.e. large deformations, twist lock opening, and stack resonance. Based on this outcome it can be

concluded that the high-fidelity codes can be used in principal for the verification of operational solvers used on board for practical evaluation of container stowage plans.

Triggered by different experience and reference values for container characteristics across class rules, it was concluded that a full-scale container stiffness experiment would be a beneficial reference for both high-fidelity and operational solvers. This experiment has been performed toward the end of the project with a 20 ft standard container and a 40 ft high cube container.



Figure 4-9: Container stiffness tests

Focus was on racking and torsional stiffness, reinforcing effect of the doors, and uplifting. Following observations are noted at this point:

- Stiffness was determined from vertical and lateral displacements at the top rail under applied loads. Displacements are determined by combined effects of uplifting and container deformations. Loads and displacements were measured.
- The container overall deformation can be represented with four degrees of freedom. Closed form expressions, linking independent uplifting at the door- and closed end, and racking at door- and closed end to applied loads and reaction loads in lateral and vertical direction, were proposed based on global uplifting, racking, torsion around the x-axis, and torsion around the z-axis.
- Measured lateral displacements were found to be non-linear related to applied loads, and exhibit strong coupling between closed-, and door-end side.
  - Large initial lateral displacements at the top rails were captured at low loads. This is due to the lever arm of container height over width, and rotation caused by uplifting as allowed by twist lock gap tolerances.
  - The doors have a strong contribution to the door end side flexibility. The contribution is non-linear due to vertical tolerances in the locking bar mechanism that allow doors to move in the seals before steel-steel contact is engaged. That allows large initial racking deformation at door end side already at low loads.
  - Uplifting and lateral racking displacements at door end and closed end side are coupled by the torsional rigidity of the container frame
  - Behaviour at higher loads up to 90 kN was found to be reasonably linear. That linear behaviour is expected to continue at higher loads under the assumption that the container can withstand ISO proof loads of 150 kN without permanent deflections.

- Typical findings observed for a load case of 87 kN applied simultaneously at door- and closed -end side of the high cube 40 feet container revealed:
  - Max uplifting of 9 mm at door end side and 15 mm at closed end side.
  - Effective lateral displacements at the top rails of 45mm at door end side, and 25 mm at closed end side. The extra deflection at door end side is caused by racking.
  - The twist lock at the closed end side carries the majority of the reaction forces due to the torsional rigidity of the container. 175 kN vs 28 kN.
  - Deformations across the diagonals by racking are order of 19 mm for the door end versus 1-4 mm for the closed end.
- Comparisons with class codes were not performed in depth. Generic observations are:
  - Class codes appear to consider an averaged constant quasi linear/elastic stiffness across the load range.
  - Class rules generally identify differences in the lateral stiffness for door and closed end sides. It is not clear if and how the coupling of the behaviour with respect to uplifting at both ends as coupled via the torsional rigidity is implemented.
  - Proper representation of the load concentrations at the closed end side require valid representation of the torsion coupling between door end- and closed end side of the container.

#### ***Main findings - Operational solver comparison***

Operational solver comparisons were done in a restricted subgroup where approach, challenges and detailed findings were discussed. All results have been collected by TNO, anonymised and subsequently reported (Ref. [15]). Below a summary of the main findings is given:

- Operational solvers are designed and tailored to assess the overall safety of a stowage configuration on a given vessel for a given voyage by calculating overall stack utilisation factors within fast calculation times.
- All solvers require simplifications and assumptions that were developed by different class societies and developers because high fidelity calculations are too time consuming for practical use.
- Because of these different simplifications and assumptions, the comparison has been performed only on the accelerations and overall utilisation factors. Interim results such as motions, individual forces and criteria are not necessarily directly comparable across methodologies.
- Effects of stack dynamics and resonant response are not considered in these calculations.
- Seven approaches to operational securing loads calculation have been compared.
- Each solver produced acceleration and utilisation factor outputs for six specified cases for a 15 kTEU vessel. A centre stack, a side stack, and a side stack with wind, all in a low GM of 1.3 m and higher GM of 3.5 m. The stack weight distribution and lashing pattern were prescribed and a 3-tier lashing bridge was present, as shown in Figure 4-10.
- The coefficient of variation of the overall utilisation factor results for each of the cases varied from 0.05-0.12 for the cases without wind, to 0.13 for the cases including wind. The majority of the results fell within a range of +/-1 standard deviation.
- Scatter in the results is as expected, because of different approaches to and assumptions for:
  - Calculation method (weakly/semi-nonlinear vs. fully non-linear).
  - One-dimensional vs. two-dimensional vs. three-dimensional approaches.
  - Design loads.
  - Accounting for the effect of lashing bridge stiffness.
  - Accounting for the effect of twist lock opening.
  - Accounting for the effect of container stiffness.

- Several possibilities for harmonisation have been identified and should be investigated further:
  - Accelerations imposed on the containers, based on a given roll / pitch amplitude and period.
  - Wind loads imposed on the containers.
  - Assumptions about container and lashing strength.
  - Assumptions about container stiffness.

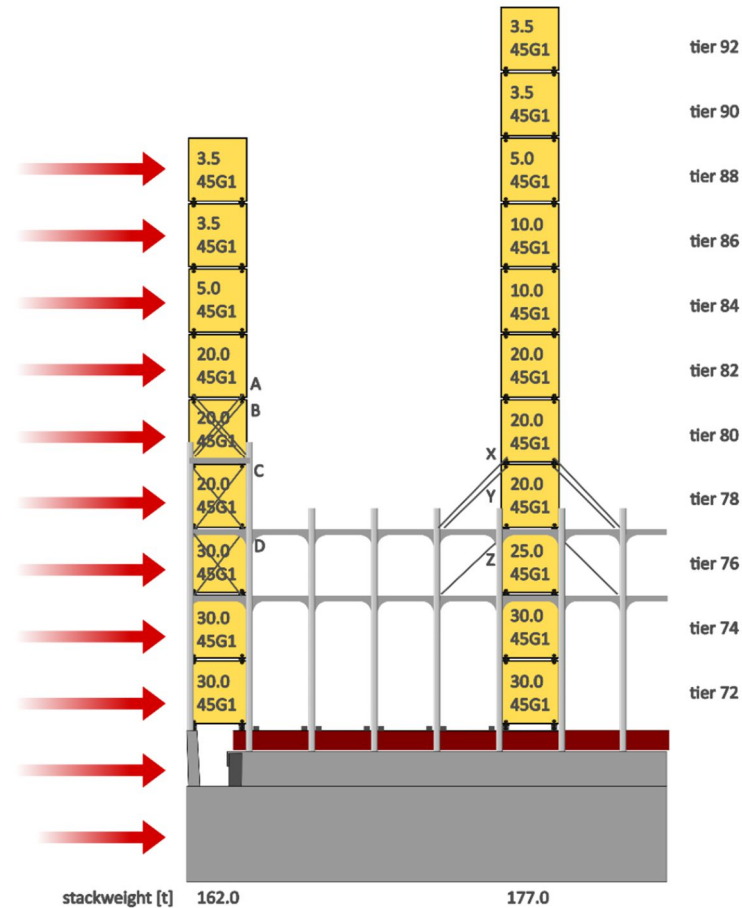


Figure 4-10: Stack configuration for operational solver comparison for a 15 kTEU vessel

#### 4.6 Vessel operation

Working Group 5 reviewed the operational aspects of vessel handling, the ability to keep in design and avoid off design conditions. The work was coordinated by MARIN and in cooperation with the participants in the TopTier JIP. The scope of work was aligned and carried out in close cooperation with Working Group 3 on vessel motions.

##### **Baseline considerations**

*"It is skill not strength that governs a ship"*. Under responsibility of the master, the vessels loading plan is prepared, checked for seaworthiness, and then the containers are loaded and secured. A voyage plan is prepared that considers the foreseeable sea and weather conditions, a route plan and potential hazards that require attention when in transit. After the departure the vessel is operated by handling speed and heading, such that motions and cargo loads stay within safe limits. Longer term route planning continues in order to avoid weather and wave conditions beyond the limits for which the vessel is prepared (Ref. [24]).

Everything on the ship is designed for a certain design envelope. This applies to the ship itself, the equipment, (lashing) gear and transported goods onboard. As long as the vessel sails within the design envelope the loads, in for example the lashing equipment, are expected to stay below the maximum securing load (MSL) limits. "In-design," refers to scenarios where the operation is within the design envelope. In this case the ship is having a predictable motion response and cargo securing forces should be within their maximum securing load (MSL) criteria. Safe operation relies on proactive monitoring and anticipating conditions and *reactive vessel handling*. The limit value of in design motion conditions should include weather and motions as considered acceptable to crew and ship. In-design motion conditions also include the conditions that cannot be avoided. The ship and cargo configuration are engineered and constructed to be capable to handle the in-design conditions. Off-design, describes scenarios where there is a risk of going outside the design envelope, i.e. above the maximum securing load of lashing equipment and experiencing extreme conditions such as excessive (hurricane) weather and responses such as parametric-, resonant- roll or severe slamming. These situations must be *pro-actively avoided* in operation to prevent potential accidents or damage.

It is the responsibility of the master to keep the vessel, cargo and crew safe (i.e. stay within this design envelope) and prevent any possible damage or failure of cargo, equipment and gear. Options to act are limited to choices for speed and heading as outlined in Figure 4-11 on the next page.

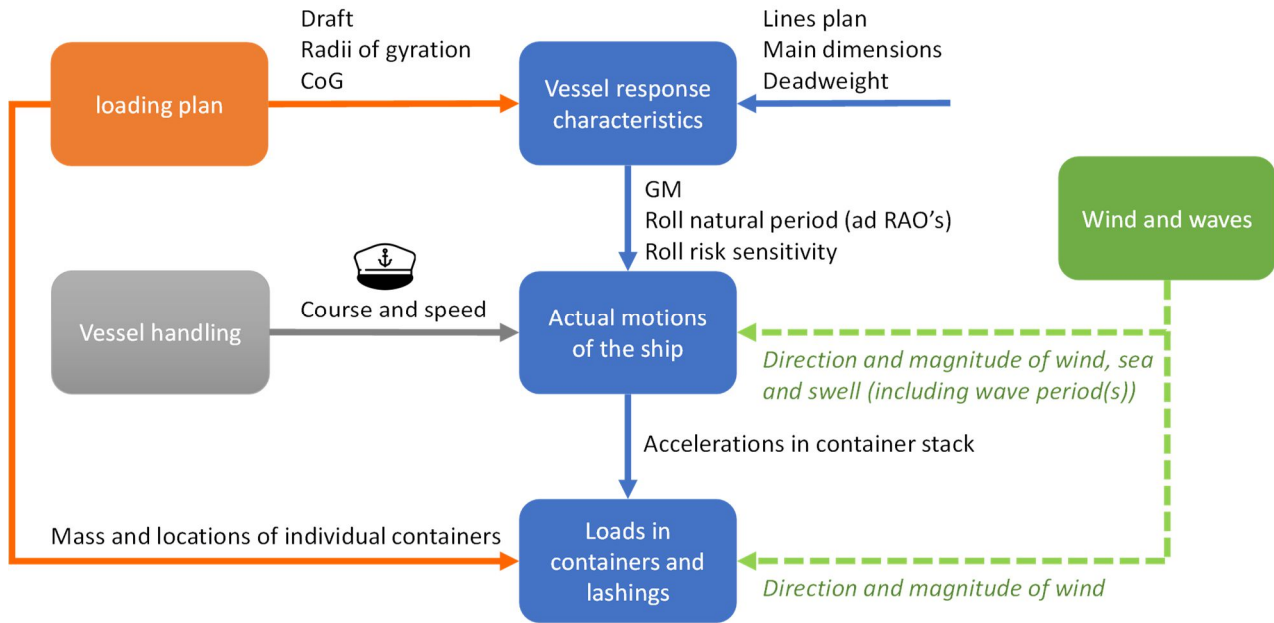


Figure 4-11: Outline of parameters influencing the loads in containers and lashings and the effect of vessel handling by the seafarer

A good understanding of the decision making process enables to provide support where it is most needed. A construct considered in this research is the concept of the OODA loop. The OODA loop is the cycle; observe–orient–decide–act, developed by military strategist and United States Air Force Colonel John Boyd. The understanding of the decision making process includes the consideration of resources available to the seafarer to enable decisions on vessel handling like information on the bridge, guidance from operator office and (onboard) decision support tooling.

### Objective

The main goal of TopTier Working Group 5 is to determine how we may support the seafarer in vessel handling preventing loss of containers. The following sub objectives are defined:

- Understand the current decision making processes on board.
- Identify the need for additional support on navigation decisions.
- Provide an overview of resources available to the seafarer.
- Identify the main obstacles complicating vessel handling.
- Suggest possible workable mitigating measures.
- Assess whether bridge crew can observe and understand precursors of parametric roll.
- Determine the response time of actions taken to prevent parametric roll conditions.
- Gain insight in the added value of information provided to prevent parametric roll conditions.
- Quantify the improvement of additional information on the decision loop.

### Scope and Deliverables

The scope of work and the deliverables in Working Group 5 can be summarised as follows:

- Survey of Crew is carried out in phase I of the project. This is summarised in a shortlist of 13 points of attentions where crew see room for improvement and confirmed and prioritised by Working Group 5 participants; see also Section 3.4. The crew survey is reported in Ref. [2], the prioritisation made by Working Group 5 can be found in Ref. [13]. The list with 13 main points of attention can also be found in the publicly available *Thank you note* Ref. [26].

- A series of incidents with exceptional container losses occurred during the winter season 2020-2021. Initial results show that parametric rolling in following seas was the predominant root cause of these incidents. Consequently the TopTier JIP took initiative to distribute a Notice to Mariners [25]. This information gives guidance to crew and on shore support for container ships on how to plan, recognise and act to prevent parametric rolling in following seas. Read the Notice to Mariners for details and a flowchart. Watch the video to learn about parametric roll in following seas. Use the calculation tool for explicit guidance.
- Building onto the items from the crew survey relating to vessel handling and the role of the crew prior to departure and during sailing the working group continued in phase II investigations which are reported in Ref. [13].
- One of the primary obstacles identified is the timely action to prevent parametric roll. To better understand the seafarers' experiences and responses to the early signs of parametric rolling and to investigate the potential added value of operational guidance, a simulator study was conducted using the MARIN Large Motion Simulator (LMS). The results of the study are documented in Ref. [10].

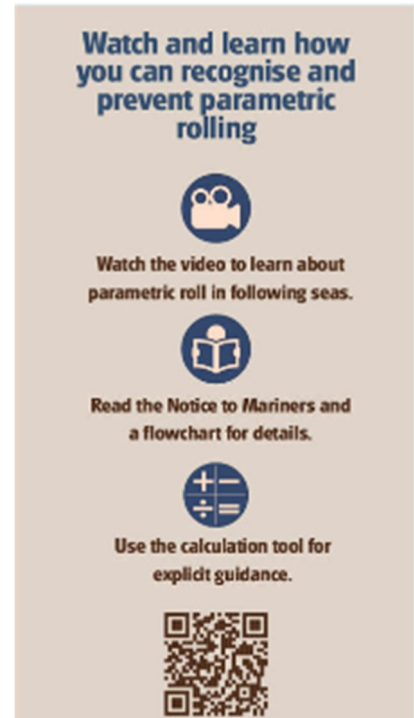


Figure 4-12: Reference to Notice to Mariners to prevent Parametric Roll in following seas

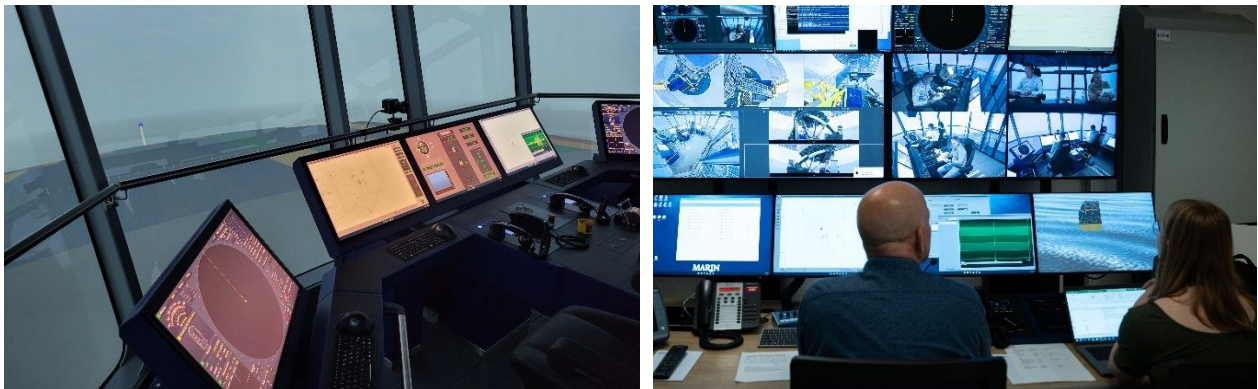


Figure 4-13: Impression of the Parametric Roll experiment on the moving base simulator (LMS)

### Main findings

In this paragraph the main findings from the above described scope and deliverables are integrated and documented. How these findings contribute to the TopTier recommendations can be found in Chapter 5.

The survey responses clearly indicate a number of areas where crews see room for improvement to reduce risk in the transport of containers, both when it comes to operations 'Prior to departure' and 'During sailing'.

The complete list of findings can be found in Refs [2], [21], [25]. Item numbers 1, 2, 3 and 4 are related to conditions of lashing material and the (influence on) the loading process and are relevant for Working Groups 1 and 2. Item numbers 5 to 12 are related to ship handling and therefore listed separately:

5. The final loading plan is often only available in the last minutes before departure or after departure and the final loading plan often does not properly represent the actual cargo arrangement on and under deck.
6. Time pressure during the loading process is high. Roughly 25% of the respondents feel a commercial pressure to depart with potential risks in loading conditions and/or planned route.
7. The roll natural period of the ship is an important factor in decision-making, yet the reliability and accuracy of the calculated roll natural period from the loading computer is limited.
8. Under way, crews operate in unpredictable circumstances with regard to weather and waves, with a lack of verifiable data about lashing conditions and loads, making decision making difficult.
9. Predicting the response of the vessel to weather is hard, especially at night, during poor visibility or in confused seas, and as a consequence crews may hesitate to take action.
10. The vast majority of respondents claim to know how to prevent, recognise and act on parametric roll but very few ever experienced parametric roll. The actions described on what to do when it happens are diverse.
11. Navigation software tools are found to be helpful, however the availability and use of tools is not uniform.
12. There is a large diversity in working methods, procedures etcetera, even within one company. Few best practices seem to be defined and there is limited opportunity to learn from each other.

Combining the information and discussions with members of the working groups results in a shortlist of primary obstacles complicating vessel handling (also reported in Ref. [13]):

- I. **Reliability of Stowage and Loading Configuration:** Delays or inaccuracies in stowage information can lead to decisions based on incorrect data. It can be seen as problematic that decisions are based on theoretical loading information deviating from reality. Without control mechanisms in place decisions might be taken on the wrong basis.
- II. **Availability of Transparent In-Design Limits:** Each voyage presents unique challenges due to varying loading conditions, which affect the vessel's response. This variation complicates the understanding of the limits in vessel handling since each voyage has different limits. This is further complicated by the fact that the voyage specific limits are not easily accessible for the bridge crew and not considered as transparent or easy to understand by the crew. See example below for some guidance on providing intuitive insights to stay in-design.
- III. **Ability to Avoid Off-Design Conditions:** The phenomenon of parametric roll poses risks for container vessels, with survey and incident investigations revealing that crew understanding of this issue is often limited. It is required to proactively avoid parametric roll risk conditions using operational guidance and clear protocols for immediate actions when preconditions for parametric roll are identified. See insights from follow up of simulator experiment on parametric roll.

Each of these items will be further elaborated in the subsequent paragraphs.

### **Reliability of Stowage and loading configuration & Roll natural period**

The roll motions of the ship are an important factor for the loads acting on the containers and lashings. In voyage planning and during the voyage, a reliable representation of the roll natural period (directly related to the GM) is therefore crucial information. Also in the risk analysis, conducted to prevent extreme roll phenomena the roll natural period is an important factor. Item 7 in the shortlist of 13 points where crew see room for improvements confirms that the roll period is an important factor in decision making. Refer to Section 4.4 and Ref. [29] for more information on accurately determining the roll natural period.

Delays or inaccuracies in stowage information can lead to decisions based on incorrect data. To mitigate this, recommendations include ensuring the final stowage plan is verified before departure, using real-time stowage data for operational decisions, and establishing robust control mechanisms to compare anticipated and actual conditions.

**Keep in-design**

An effective approach to intuitive onboard guidance regarding in-design conditions involves offering clarity on what constitutes 'in-design' while incorporating monitored data to put the control loop in place. Evidently it is essential to align crew training with standard operating procedures. This allows the crew to receive operational guidance that clarifies how the current situation or condition compares to the design limits. In the context of container shipping, operational guidance for maintaining in-design conditions could include the following:

- **Transparent limits** – that the stowage and lashing configuration is designed for are provided;
- **Reliable information on present state** – is available by monitoring;
- **Procedures** – on the actions to be taken when limits are exceeded are defined;
- **Training** – or other means of education on the way of working is provided.

The following main categories of information may be distinguished: 1) Motions of the ship; 2) Loads in containers and lashing. The loads are induced in particular by lateral accelerations from rolling motions of the ship combined with the roll period. The apparent roll angle of the ship as indicated by the clinometer on the bridge is an intuitive measure that combines roll motion, period and lateral acceleration in one. The seafarer can directly observe and determine the ship's rolling angles, which provide an intuitive experience that can be further explored and expanded upon. Operational guidance provided by an onboard instrument should display both the current roll angle of the ship and the maximum limit. This requires insight and availability in the design roll angle and acceleration that was used for stowage planning. Furthermore, the information on the present state of ship motions could contain a forecast of the expected motion levels based on the route plan and forecast conditions.

Direct measurement of loads in containers and lashing would allow for direct comparison with safe working loads of the equipment. Monitoring forces in containers and securing arrangements directly during operations are however a complex task. Alternatively, the forces might be derived with the algorithms in the lashing software using the stowage plan information combined with measured motions. This might be less intuitive for seafarers than the previous method of providing operational guidance on motions directly. Examples of such systems are referred to a *lashing load calculator* or *lashing monitor*. A user-friendly interface and training should be considered in this respect.

**Prevent Parametric Roll Off-design conditions**

Parametric roll is one of the off-design conditions a containership might encounter. In this project significant effort was put in understanding and improving the prevention of parametric roll since it is the root cause of major incidents as described in Chapter 3. Parametric Roll is an 'ill-behaved' phenomenon. The moment it occurs, and especially the maximum roll angle into which it develops, are difficult to predict. When the right wave preconditions are met, parametric roll starts, and roll angles increase rapidly to potentially extreme angles. There might be only a couple of oscillations between insignificant 'noise' and angles above 30 degrees.

Acting only once the roll angle already exceeds a certain limit does not allow sufficient time to change course or speed. To prevent it, parametric roll preconditions should ideally be avoided in advance. The occurrence of parametric roll depends on the combination of the natural roll period of the ship and wave encounter period. However, there might be situations when all the information needed to predict the onset of parametric roll is not reliable or available in time or there are no options to change course or speed. Therefore, it is not always possible to completely avoid getting into conditions that are too close to parametric roll preconditions.

Table 4-3: Prevent parametric roll on strategic, tactic and operational level

Level	Phase	Action when preconditions are met	When
Strategic	Voyage planning	i. adjust route ii. adjust loading*	Prior to departure
Tactics	During sailing	adjust route	Regularly, e.g. with update of weather**
Operation	During sailing	change course or speed	Immediately

\*) adjust loading = change GM to influence the roll natural period

\*\*) for example with an update of the weather forecast

Insight gained from onboard measurements clearly show that first signs of parametric rolling already occur hour(s) before the ship reaches extreme roll angles (see time trace from an onboard measurement in Figure 4-14). Therefore it is important to recognise the preconditions for parametric roll, acknowledge the risk of parametric rolling, know what to do, make the appropriate decision and act. In hindsight this could have made a difference in recent incidents.

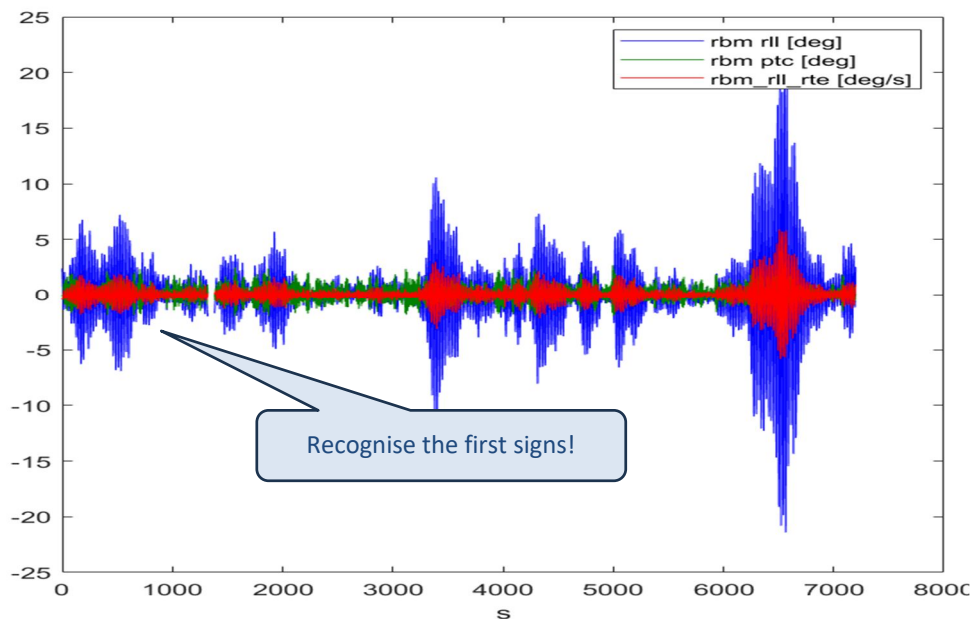


Figure 4-14: Example Parametric Roll in onboard measurement

A parametric roll experiment was conducted on MARIN's moving base bridge simulator. Participants underwent controlled experiments designed to evoke conditions conducive to parametric rolling. Participants completed multiple experimental runs under various wave conditions and different levels of available information.

Results indicated that crews struggled to consistently identify precursors of parametric rolling and lacked full understanding, despite self-reported high situational awareness. Decision-making patterns varied, influenced by familiarity with tools, trust in personal judgment, and external pressures. Additional information systems, such as the parametric roll risk polar plots (Figure 4-16), improved awareness and decision-making efficiency. However, timely actions were often delayed due to reliance on personal feeling or waiting for worse conditions.

The following recommendations can be made:

- The preconditions of parametric rolling are difficult to recognise, independent of the level of experience of crew and previous experience with parametric rolling.
- Operational guidance in the form of a decision support tool (like the polar plot, Figure 4-16, and historic roll/pitch graph - both the timer-trace as well as the “butterfly”, see Figure 4-15) on board has shown to be of added value.
- Understanding the risks associated with parametric rolling is a crucial element in the readiness to take action.
- Introduction of operational guidance/decision support system requires procedures and working standards. These should be into place on both the operational level and on a company tactical level.

It is important to note that the butterfly graph illustrated in the diagram below is derived from a model test experiment. A comparable plot can also be generated using onboard measurements; however, in that case, the butterfly shape may not appear as clearly as in the example shown. Nevertheless, the distinctive eight-figure pattern with intersecting lines can still be identified. Furthermore, the characteristic motion is recognised as intuitive and self-explanatory by the mariners participating in the experiment. Additional effort is required to determine the best way to scale and present the plot effectively.

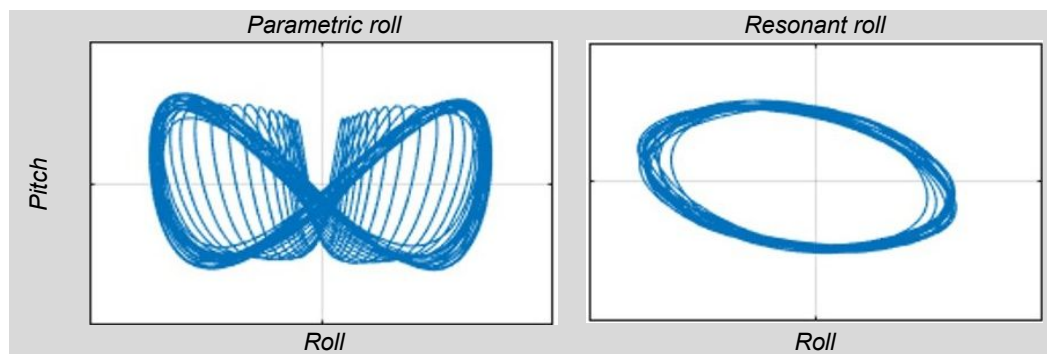


Figure 4-15: Parametric Roll - phasing of roll and pitch – the Butterfly

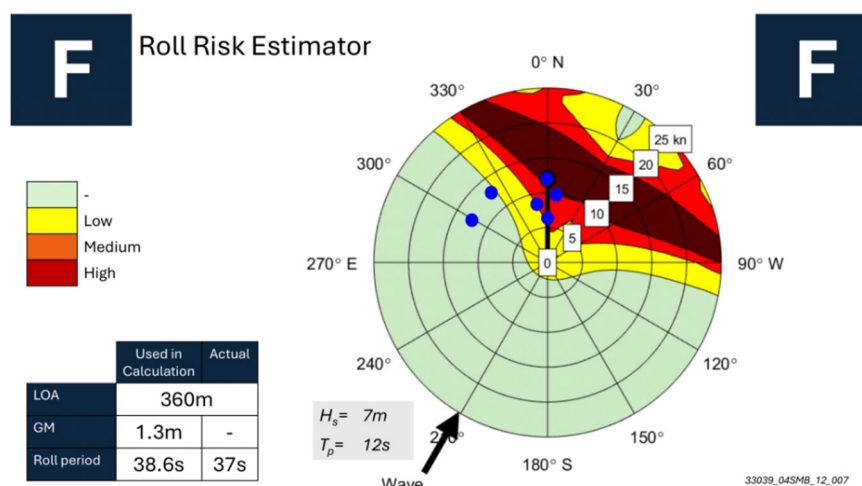


Figure 4-16: Parametric roll risk estimator (blue dots indicate actions in experiment)

#### 4.7 Regulatory aspects

The TopTier proposal explicitly aimed at sharing its results with IMO, ISO, ILO and IACS in order to ensure its impact on the safety of container shipping through implementation of its recommendations in the relevant regulations and standards while maintaining a level playing field.

##### Contacts with authorities to date

The original planning of TopTier envisaged to bring project findings to the attention of regulating authorities towards the end of the project. That was pulled forward in time in response to requests by the participating national authorities, WSC and others that advocated the need for close engagement with the IMO from the initial stage. Formal submissions to IMO were prepared to notify MSC and keep up with the ongoing process at IMO during **MSC 106/107 (Nov.2022/June 2023)** which agreed on two related outputs for inclusion on the agenda of the MSC subcommittee on Carriage of Cargoes and Containers (CCC). ), i.e. *Revision of the Revised guidelines for the preparation of the Cargo Securing Manual (MSC.1/Circ.1353/Rev.2) to include a harmonized performance standard for lashing software to permit lashing software as a supplement to the Cargo Securing Manual and Development of measures to prevent the loss of containers at sea.*

In the course of the project both the IMO and IACS took observer status. Contact with ISO was established via project stakeholders that were involved in technical committee TC104 dealing with standards for containers and lashings. Contact with ILO was not established within the project.

Prior to these developments TopTier delivered an update on the progress of the project at MSC106 (**MSC.106/INF 16**) accompanied by a **presentation** at MSC 106 raising awareness about TopTier. To the subsequent **CCC-9** meeting (**Sep. 2023**) an INF paper was submitted summarising the progress within the three project phases:

- Phase I; A review of current practice, overview of incidents, feedback from crew on board and a gap analysis (data collection).
- Phase II; The working groups' progress on strength of container and lashing gear, on mis-stowage and container mass, on in-off design motions, on calculation of stack & lashing forces and on crew governing support.
- Phase III; Overview of potential updates of regulations and standards.

In the aftermath of CCC-9 the two outputs as indicated above were placed on the agenda of CCC-10 and it was decided to establish an intersectional correspondence group (ISCG) dealing with prevention of the loss of containers at sea which combined these two agenda items. CCC-10 (Sept. 2024) established a drafting group which prepared Terms of Reference for the ISCG, making the timely submission of proposals on these agenda items, based on TopTier results, highly relevant.

The TopTier submission consisted of three documents:

1. DEVELOP MEASURES TO PREVENT THE LOSS OF CONTAINERS AT SEA.  
Review of incidents resulting in loss of containers (CCC 10/INF.17).
2. DEVELOP MEASURES TO PREVENT THE LOSS OF CONTAINERS AT SEA.  
Summary of incident review and gap analysis (CCC 10/INF.18).
3. DEVELOPMENT OF MEASURES TO PREVENT THE LOSS OF CONTAINERS AT SEA.  
Improvements to be considered for the safe transport, stowage and securing of containers. (CCC 10/11/5).

The latter paper lists the following aspects for further consideration:

- Fatigue of crew during cargo operations.
- The exceeding of design parameters related to ship motions which are not considered in stowage planning, through enhancing crew awareness and provision of information on voyage specific data.
- The requirement of correct representation of actual container stowage by validation of planned positions and weights as considered in the validation of the safety.
- The integrity of containers through improved oversight and control of the condition of container structures.
- The integrity of lashing gear through oversight and control of container lashing gear.
- The proper packing of containers through promoting the use of the existing CTU code.
- Harmonised performance standards for and proper use of lashing software supporting voyage-specific assessment of the cargo stowage and lashing integrity.

The drafting group, incorporated the proposed aspects within the Terms of Reference (TOR) drafted for the correspondence group for further consideration between CCC-10 and **CCC-11 (Sept. 2025)**. See also the added TOR in the annex of the WG 6 report.

Interaction with ISO is established through project stakeholders that contribute in the discussion around revision of standards for containers, corner castings and twist locks.

### **Continuing interactions with IMO**

“The TopTier participants agreed that the present final report should be submitted to CCC 11 so that its results and recommendations could be taken into account during IMO work on measures to address containers lost at sea and lashing software”.

Roles and training requirements for stakeholders involved in stowage planning, loading, securing and supervision should be further elaborated e.g. for

- Ships loading and bridge officers involved in planning for expected voyage conditions, vessel operation using decision support systems as considered in planning etc.
- Shore side staff involved in planning and loading.

TopTier project management intends to stay in contact with the TopTier members on the above aspects.

## 5 CONCLUSIONS AND RECOMMENDATIONS

This chapter combines the key findings from the research output as outlined in Chapter 4. It starts with overall observed conclusions and then proceeds with recommendations. The recommendations are categorised into two sections: one that is anticipated to be achievable in the near term, and another that is expected to take a longer time to implement but is required to make container shipping future proof.

### 5.1 Overall conclusions

Based on the main findings the following conclusions can be justified:

- Performance and safety levels of container transport should be further enhanced.
- Container stowage safety is handled by assessing proposed stowage plans against acceptably safe criteria. A harmonised criterium for acceptably safe container stowage however is not defined.
- The validation of safe stowage relies on compliance of the actual stowage that is loaded on board with its digital representation that is provided by the terminal. Options for control and enforcement of that compliance are limited in current practice. Confidence in the actual execution of an agreed stow plan is critical.
- Practical day to day stowage validation is based on and determined by “utilisation factors” representing the ratio of expected- and maximum allowable force.
- Worldwide practice and class rule implementations for software that calculates utilisation factors, have converged such that safety constraints do not unreasonably restrict cargo intake.
- At the same time, however, public perspective towards overall loss of containers calls for improvement. Target should be zero loss of containers at sea.
- An explicit criterion for “acceptably safe” is missing. But the following factors must be taken in to account:
  - An operational approach through Utilisation Factors (UFs) has become widely adopted over past decades through lashing software. The concept of planning up to a 100% max. allowable criterium, is practical, clear, and is not disputed.
  - However, the confidence that forces won’t exceed allowable limits, and that allowable limits align with true strength in practice is currently unclear.
- To bring down container loss at sea, this confidence must improve. That calls for the following objectives:
  - The probability that actual securing forces exceed the calculated worst expected values must be reduced.
  - The probability that actual strength of the securing arrangement is less than the safe allowable load used in the calculation must be reduced.
- Reducing the probability that actual securing forces exceed worst predicted loads calls for improving crew options for awareness, and control over hazards and limits:
  - A majority of container losses over past years was directly caused by excessive vessel and stow behaviour that supposedly could have been avoided by vessel handling. It is essential to prevent the potential occurrence of extreme behaviour.
  - Simulations detailed in the report reveal the negative impact of mis-stowed containers and VGM discrepancies (overweight) in the actual load versus calculated predictions. Responsibilities, control and options for verification of stowage position and oversight over VGM requirements, must be improved. The digital representation should be identical to reality.

- The seaworthiness of the ship and safety of container transport as suggested by a 100% utilisation factor will never be absolute. Crews must be able to recognise if operating conditions approach or exceed the design envelope that was considered for load prediction calculations.
- That requires clear and intuitive information on limiting sea states considered, maximum motions and accelerations expected, and awareness to act accordingly.
- Clear and harmonised parameters must be defined for interaction between crews and software in terms of waves, roll angles, periods, accelerations etc. E.g. single peak amplitudes, significant values, 3-hour – 20-year extremes, natural periods, mean periods.
- Factors with respect to the probability that actual strength is less than the considered values are as follows:
  - Effective Safety Margins are tight. The effective safety margins of lashings and twist locks are less than the factor 2.0 that is referred to in lashing equipment standards. The effective strength is limited by the container as the weakest link since there is no safety margin on the ISO proof load. The effective safety factor for lashing+container (in newstate) is around 1.2 to 1.3.
  - Different types of twist locks have different nominal holding forces, and different scatter in repeated tests due to dimensional tolerances, and sensitivity to small variation of alignment.
  - Dimensions of container corner fittings exceed ISO and CSC standards in practice surveyed data.
  - Inspection and maintenance of lashing gear and containers relies on owners. Overarching oversight regimes like statutory-, flag state- , and port state control fall short due to the impracticality to perform on site inspections.
- Methodologies / algorithms used in loading calculations are aimed and tuned to provide best practice Utilisation Factors. Intermediate results for calculated forces and allowable loads are not separately compatible or straightforward relatable to actual loads, motions or other crew observable criteria.
- Conclusions regarding regulations around cargo stowage and securing are as follows:
  - Container ship stowage planning, validation for seaworthiness, loading, securing, and oversight over proper loading progress is a complex workflow involving multiple actors and stakeholders. Regulations do not cover all roles, the full chain of responsibility and requirements around control and enforcement. That makes it difficult to identify the responsibilities between stakeholders on ship and shore side. (E.g. for planning, loading and departure stowage plans, VGM, condition of lashing gear and containers).
  - Regulations do not recognise, regulate or provide guidance for the use of lashing software based on utilisation factors. Different implementations of lashing software algorithms and their intermediate results are not directly compatible.
  - The specific aspects of containership planning and loading operations are not included in training requirements for ships' crew and terminal planners. E.g. the concepts and challenges of safe container stowage, the distribution of roles and responsibilities for planning, loading, securing, stowage validation, vessel handling, the use of lashing and decision support software tools.

## 5.2 Recommendations

Container shipping is an international trade. Overall safety of shipping, seafarers, ocean and coastal environments, relies on improving performance of world fleet and ship shore operations worldwide. The following recommendations are a mix of process improvements, and suggestions on how these could be anchored in regulatory frame work.

The recommendations are categorised into two sections. The initial set of recommendations includes prioritised items that are upgrades in line with the current practice in container shipping and can be readily implemented for short-term improvements.

and another that is expected to take a longer time to implement but is required to make container shipping future proof. The implementation of the second set of recommendations will demand more time and to some extent a new approach, but it is essential for ensuring the long term safety of container shipping.

### 5.2.1 Short term recommendations

- **Implement decision support / operational guidance for proactive avoidance of off-design.** To avoid ship motions in excess of the worst “expected” extremes as considered in planning calculations. The 2<sup>nd</sup> generation intact stability code (2GISC) calls for operational guidance in case risk for extreme motions can’t be ruled out according to level 1 or 2 approaches. Container stowage planning calculations can however also consider beneficial effects of weather routing, and crew interventions that may result in reduced “off design” conditions compared to the 2GISC limits. Decision support and operational guidance should be in place in case these are needed to achieve that. Since multiple approaches are possible, the recommendation is not “how”, but “that” decision support is handled. Typically by requiring that the CSM/ISM should outline both 1) how the “in design” conditions considered in stowage planning are determined (e.g. using approved lashing software and voyage preparation), and 2) how worse “off design” conditions that could occur are actively avoided. E.g. by means of training, availability of forecasted or measured wave/weather data, seakeeping monitoring and prediction tools, and mitigate accelerations due to hull girder dynamics that could trigger stack resonance since best options to avoid stack response are not clarified etc. This should incentivise industry to develop, support and train for active avoidance of extremes by parametric roll, and excessive sea states.
- **Ensure the agreement between “digital representation” – “actual stowage”.** This requires increased confidence in the stowage positions of individual containers and VGM weights in EDP/BAPLIE file stowage plans. That relies on the quality and control of information that is exchanged between many stakeholders involved in loading. The project did not agree on a single recommended solution. Recommended that discussion on this issue proceeds (e.g. in IMO, or outside between industrial stakeholders). Following options are listed for consideration .
  - Formalise a description of roles and chain of responsibilities for stowage planning starting with a clarification of the obligations of terminals loading the containers aboard ship.
  - Minimum objective is to have adequate control and enforcement to ensure compliance. Checking 100% of overall volume and alert for individual outliers may be not necessary.
  - Involvement, roles, and responsibilities for shore side stakeholders should be further considered with a view to identifying realistic measures and initiatives. Similarly, vessel specific operational solutions should be further considered and ultimately be defined via the CSM.
- **Recognise the use of “On board lashing software”** that is widely used already. It facilitates flexible and efficient operations. Harmonised performance & functional standards however have to be agreed. Following minimum requirements are recommended for consideration:
  - Objective: to assist the master/loading officer with validation of stowage plans for seaworthiness by calculation of normalised Utilisation Factors of the proposed stowage plan under reference extreme conditions as expected in the voyage.

- Provide crew with clear information for the considered voyage extreme conditions (e.g. expected worst waves and motions) along with the calculated utilisation. This to enable operating decisions relative to a clear maximum envelope.
- Define a harmonised / baseline probability of exceedance that is considered acceptable for actual loads to exceed allowable limits when UF is 100%, and include that in LSW performance standards.
- Definition of and compliance to harmonised performance standards for solver algorithms with respect to accelerations, wind loads, stiffnesses and strengths of containers and lashing gear. (as also presently under discussion in the IMO ISCG).
- **Maintain status history from inspections on fixed and loose lashing gear** over time, rather than maintenance logs alone. This reduces the probability that wearing out of ships lashing equipment gradually over time is not recognised at an early stage.
- **Persuade / stimulate container owners to increase focus of Periodic Examination Schemes (PES) and Approved Continuous Examination Programs (ACEP) on inspections** of container corner casting opening tolerances since these can have negative impact on fully automatic twist lock (FAT) performance.
- **Incentivise terminals to provide independent feedback on ships lashing inventory**, container conditions, VGM, and stowage positions of discharged cargo in comparison to arrival stowage plan.
- **Encourage flag states and other relevant IMO member states to investigate and make public reports also on small-scale container loss incidents** considering that, currently, root causes and impact of such more frequently occurring small-scale incidents are underrepresented in existing publicly available incident reports.

### 5.2.2 Longer term recommendations & future work

- Continue investigation into the development of multi bay stack resonance. The excitation as well as the responsive phenomena are demonstrated in TopTier research. A large part of medium scale incidents are attributed to this phenomenon. Objectives aiming at:
  - Minimise plausibility to trigger stack resonance by ambient flexible hull vibrations. Check the feasibility of favourable planning of dynamic properties of adjacent rows in the bay.
  - Mitigate development of triggering excitation loads from horizontal bending and torsion in the hull girder by choosing favourable heading and speed.
- Consider extending the role of container terminals with regard to verification of container- and lashing gear conditions as well as stowage positions in order to enable control and enforcement options. E.g. using logs of VGM compliance, lashing gear ratings, stowage positions (pending further discussion).
- Promote information exchange between load planning software, operational guidance software, and long term inspection and maintenance records. Extend calculated normalised Utilisation Factors ( $UF = F_{max\_expected} / SWL$ ) with underlying extreme conditions, loads and safe working loads. That will allow evaluation of transit motion conditions to planned assumptions, and nominal performance of lashing gear from long term inspection and maintenance to the performance considered in planning calculations.
- Develop a more fundamental methodology for the assessment of a safe stowage. Breaking down the unfortunate probability of stowage failure, in the separate contributions of voyage specific aspects by stowage, route preparation, safe motion levels and vessel handling, and the long term characteristics of lashing gear and container performance via inspection logs and tests against reference standards. Typically including:

- Develop realistic probability distributions for motion/force levels at design sea states by combined regular seakeeping motions, and increasing hazard for off design conditions in raising sea states. (simulated data, or experience using measured data). Carriers, class, technology institutes.

- Develop characteristic probability distributions for combined lashing+container failure as function of load level. Accounting for type, condition, age and wear of containers and lashing gears. Makers, ISO, technology institutes, class.
- Overall probability of failure. (Allowing feedback to practice).
- Start follow up discussion with stakeholders to evaluate merits and options to:
  - Improve control and enforcement over the inspection and maintenance regimes for containers by means of long term condition logs over time. E.g. by maintaining a digital container twin in a centralised data base as Boxtech, for container condition information, equipped with API to request and submit specific information by authorised users.
  - Increase practicality of oversight, control and enforcement of shipper responsibility over container VGM by recording logs of declared and measured weights.
  - Increase confidence in a lashing gear condition baseline, by raising the practicality of insight, control and enforcement of inspection and maintenance regimes, e.g. by maintaining long term logs of condition history including feedback from stevedores that handle the equipment.
  - Quantify the expected improvement of these measures on operational safety.

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### TopTier internal deliverables

Below list of deliverables are TopTier internal deliverables which cannot be shared outside the TopTier group.

- [1] WG0<sup>2</sup>, Koning, J., *'Review current practice'*, MARIN 33039-2-PaS, Jul 2022
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- [3] WG4, Suzuki, S. et al, *'Container stack model tests'*, MTI J-0022-E, Sep 2022
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- [21] WG3, den Hollander, J., *'Onboard measurements'*, MARIN 33033-8-PaS, Jun 2025
- [22] WG4, Koning, J., *'Experimental assessment of 40&20ft container racking & torsion stiffness'*, MARIN 33039-16-PaS, Mar 2025

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<sup>2</sup> Note that WG0 refers to deliverables not linked to a specific working group

### TopTier public deliverables

Below list of deliverables are TopTier public deliverables which are public deliverables and free to distribute externally and available on <https://www.marin.nl/en/jips/toptier>.

- [23] WG3, Grin, R., *'Review of incidents'*, MARIN 33039-1-SEA, May 2022
- [24] WG0, Koning, J. et al., *'TopTier, seakeeping and container cargo securing safety'*, 18<sup>th</sup> International Ship Stability Workshop Gdansk, Jun 2022
- [25] WG0, TopTier, *'Notice to mariners; beware of parametric rolling in following seas'*, Jul 2022
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