Snapback Characterisation for Arresting Structure Design: Physical Testing Insights

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Summary
Mooring line snapback presents a dynamic challenge, transferring significant kinetic energy to any structure in its path. Despite its importance, specific design guidelines for mitigating snapback risk remain absent. Current analogies from related industries offer some guidance but fall short of fully capturing the impact of high-velocity mooring line events, potentially leading to inadequate solutions. This paper emphasizes the necessity of understanding snapback characteristics to inform the effective design of arresting structures. Through detailed exploration of mooring line behaviour during a snapback event based on physical testing as discussed by Hodgins K (2023) in her paper “Validating Snapback Risk”, this study aims to build on existing theory and fill gaps in knowledge. By grasping these dynamics, the paper seeks to facilitate the development of practical solutions to mitigate risks associated with high-energy snapback events. Ultimately, this research contributes to enhancing personnel safety, productivity, and efficiency in maritime operations.

Keywords: snapback, mooring lines, life safety, ports, arresting structures

1. Introduction

Assessing the impact severity resulting from a snapback event poses a multifaceted challenge. Various factors contribute to the magnitude and characteristics of these impacts, including the mooring line material, composition, and manufacturer, rupture location, breaking tension, and trajectory. Additionally, the way the line fails, often influenced by the mooring configuration, heavily influences the nature of the impact event. Sweeping failures (ref. Figure 1), prevalent in spring or breast lines, often travel along a three-dimensional trajectory, generating complex side-swiping impact events and unpredictable hazard zones, over expansive areas. This is discussed by Butler J, (2023) in his paper “Loose Ends: Computational Modelling of Snapback Paths” Meanwhile, direct line failures in head lines or stern lines often travel along a two-dimensional trajectory, at least initially, following the path of the moored line toward their termination point and generating concentrated impact events within confined areas. However, if the ruptured line collides with obstacles in its path, deflects off a surface, or is propelled off accumulated ruptured rope at the termination point, it can suddenly shift into a three-dimensional trajectory, resulting in impacts and hazard zones more like a sweeping failure.

Figure 1: A snapback event penetrating a conventionally designed operator cabin with multilayered toughened glass during base line testing - Keane R, (2024).

Relying solely on conventional methodologies and parameters to gauge impact severity, risks oversimplification of the event, and may lead to ineffective arresting structures. For instance, the mere consideration of the weight and velocity of the tail section, or the deceleration of a ruptured line alone, fails to provide a comprehensive understanding of the impact dynamics. This approach, relying on analogies from neighbouring industries, may overlook crucial factors, potentially leading to inaccurate assumptions regarding the severity of impacts that result in over-engineered structures or unforeseen failures (ref. Figure 2)

Figure 2: A temporary arresting structure developed using conventional methods, unsuccessfully arresting ruptured line - Smith A.S, (2021).

2. Conventional structure design

Most structures that are required to withstand large loads are typically designed with a linear response to statically or dynamically applied loads. These structures operate predominantly in the elastic response region of the materials and structure. Excess plastic deformation, or rupture, is considered a failure of the structure’s performance. Conventional structures are often designed to withstand large static loads over a long duration throughout their design life, which typically spans many years. They do so by using specifically selected combinations of material strengths and structural layouts for component-to-component load transfer. Examples of such structures include buildings or bridges.

Such structures may be required to withstand large dynamic loads, such as seismic loads on buildings, or bridges with significant applied 'live' loads. These structures do so with a predominantly linear response, with some provision for small-scale, localised, low strain plastic deformation. Significant plastic deformation of the material or large, non-linear response of the system is typically considered as an unacceptable characteristic. Consequently, conventional engineering methods used to design these structures employ first principles of elastic response, low displacement analysis, and low strain-rates to predict responses of the structure. Tools such as engineering calculation, implicit (linear) FEA and small or medium scale physical testing are used to apply static or pseudo-static point loads to predict linear response.

2.1 Assumptions

Conventional approaches to the design of structures often require simplification or assumptions to be made for the loading applied to the structure. In an attempt to predict the severity of a mooring line impact and the likely performance of the arresting structure, current general practice in the industry is to utilise conventional methods of linear response, with certain key assumptions about the applied load. These in turn have some notable limitations. For example:

- Predicting response using force

  $$f = ma \qquad (1)$$

  Where f = force, m = mass and a = acceleration.

  Assumptions are made on the stopping distance and linear reduction in impact speed, to determine acceleration.

  Limitation - does not easily account for forces that may change over the time of impact (e.g. when a structure is designed to flex or move during loading)

- Predicting response using stress

  $$\sigma = f/a \qquad (2)$$

  Where σ = stress, f = force and a = acceleration.

  Assumptions are made on the cross-sectional area of loading.

  Limitation - does not easily account for compounding loading events from a single snapback impact.

3. Practical considerations

To accommodate for inaccuracy inherent in key assumptions, conventional methods often apply a large safety factor to accommodate for the uncertainty of actual loading applied. For designs with a life safety component, factors of up to 10 x may be applied. With this approach, the instinct may be to design structures with unlimited strength and size to withstand snapback events. However, such a design approach results in bulk, weight, and cost. Practical considerations within environments such as commercial terminals (ref. Figure 3), operating ports, offshore platforms, and vessels, present significant challenges to such an approach. The following are some examples of these considerations:

- The need to maintain high visibility for personnel through any arresting structure.
- The need for personnel movement in, and around the structure to enable mooring operations.
- A limited footprint or space to install an arresting structure.
- A limited exiting structural capacity for the installation of an arresting structure.
- The need to keep operations online, meaning short windows of time for installation.
- A limited access for heavy equipment to install locations.
- Harsh metocean conditions such as high wind loading, extreme UV, and saltwater.

Figure 3: Hay Point coal terminal (BHP Mitsubishi Alliance - BMA, Hay Point Mackay)

3.1 Debris

Debris resulting from a snapback event presents a danger of causing significant injury or death. Even when a mooring line fails to penetrate an arresting structure, resulting debris can pose a significant danger as seen in Figure 4; a small metal segment broken from a structure due to an impact with a ruptured mooring line can travel at exceptionally high speeds, more akin to a fired bullet.

Figure 4: Debris 5 recovered during snapback testing of a non-proprietary rigid arresting structure - Keane R, (2024).

Examples below that were observed in testing illustrate the weight and velocities of debris from a broken structure (Table 1). A .22LR rifle projectile is included for comparison.

Table 1: Recorded snapback debris from testing of a non-proprietary rigid arresting structure - max velocity, weight and max energy (Keane R, 2024)

Debris Code	Max Velocity (m/s)	Weight (g)	Max Energy (J)
1	57.7	53	88.3
2	152.5	46	534.9
3	143.7	52	536.9
4	76.6	38.5	113.0
5	110.5	101.5	619.7
6	67.7	46.0	105.5
.22LR Projectile	330.0	2.6	163.0

4. Energy methods

Anecdotally there is recognition in the industry that conventional structural methods may not be well suited to analysis and engineering of snapback arresting structures. In an attempt to recognise the energy nature of these events, an approach of analysis by considering the kinetic energy of the ruptured rope's end (to be arrested) is applied. The force response of the arresting structure, with respect to distance deflected, might then be used to determine the energy capacity of the structure to withstand the impact energy.

While energy methods are valid for the analysis of deformable systems under loading from moving objects, the approach has significant limitations when considering high-rate impacts with a flexible whip element.

For example:

- Predicting response using kinetic energy

$$E = 1/2mv^2 \qquad (3)$$

Where E = kinetic energy, m = mass and_v = velocity.

Assumptions are made on the mass of the impacting section, previously assumed as approximately 2m in length, and that the impact event is a singular event. The velocity of the section is determined at a single time point (i.e. initial impact).

Limitation – the effective size of the impacting section can be defined in multiple ways (i.e. elbow, tip or complete tail). This can also vary significantly, depending on the type of failure, the resulting trajectory of the line, and the consequential contact length of the ruptured section with the arresting structure. In turn, this heavily influences the mass of the impacting section and the resulting tip velocity, thereby effecting the predicted impact severity when applying this method. Further, the concentration (or spread) of loading on any given region is also not accounted for, where properties of the following line segment continue to impact the arresting structure.

- Absorption by bulk deformation of structure

$$1/2\, mv^2 = f.d \qquad (4)$$

Where m = mass, v= velocity, f = force and d = distance.

An assumption is made that the structure's bulk strain response (pseudo-dynamic loading) can absorb the kinetic energy.

Limitation – while true under low impact rates, during highly dynamic events the inertial effects of the structure's material and elements significantly affect the dynamic deformation of the arresting structure. Where a low loading rate has time to move and deform surrounding elements and distribute the deformation (absorbing energy) through the bulk structure, the rapid nature of the snapback event sees inertial effects limit the deformation to a more localised region. The assumption does not account for the absorption of the impact energy over a smaller region with the effect of increased strain on a localised region.

- Application of 'tensile data' in high strain events.

The assumption is that the stress-strain response (and data) of materials tested in pseudo-static loading apply at high strain rates.

Limitation – This assumption does not appreciate that some materials exhibit differing stress-strain responses as the strain rate of loading increases. At high rates material strengths and/or failure deformation limits may change, reducing the energy absorption capacity of the material compared to that suggested by the 'tensile data'.

5. An alternative approach to structure design

When considering the highly dynamic, high-energy nature of a snapback impact, an alternative approach to designing structures by utilising nonlinear loading and response provides a more suitable option. Unlike conventional structural designs, structures with a nonlinear response are best designed to withstand and absorb energy, and large dynamic loads over much shorter periods of time (seconds), using controlled plastic deformation in addition to a combination of material strength and component-to-component load transfer. Examples of applications where such methods are applied effectively include roadside safety barriers or crash rated security barriers. These methods do not rely on calculations and engineering analysis where the use of simplifications and assumptions, surrounding the loading event and precited response, is afforded. Consequently, the engineering methods by which they are designed are more complex. In addition to elasto-plastic material properties, large-displacement engineering calculation tools include explicit (nonlinear) FEA and full-scale physical testing to apply complex dynamic loads and accurately validate nonlinear responses (ref. Figure 5, 6).

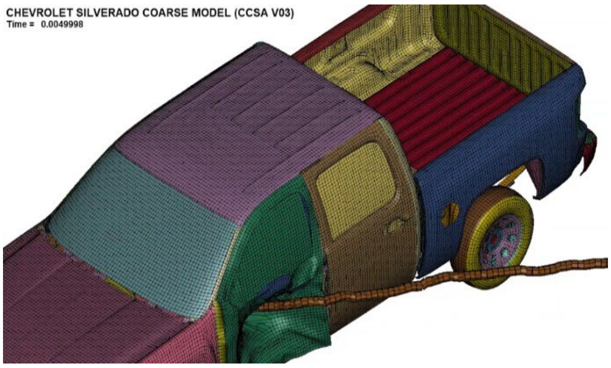

Figure 5: Non-Linear FEA snapback simulation result - Wong C, (2023)

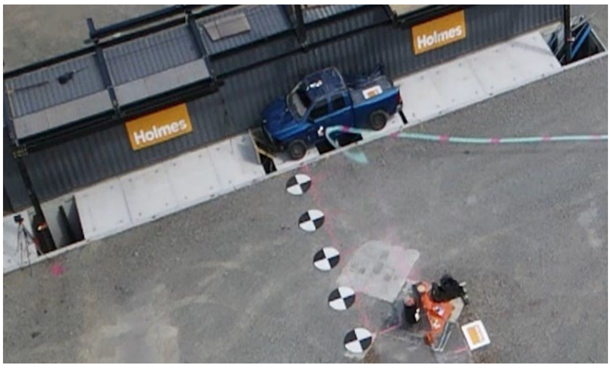

Figure 6: Universal full-scale snapback test setup during research test examining impacts with vehicles on berths - Holmes Solutions, (2024)

6. Understanding snapback impact severity

There are some significant differences between the types of impacts that structures such as roadside safety barriers or crash rated security barriers are designed to absorb, and the types of impacts resulting from a snapback event. Specifically, impacts resulting from a snapback event occur at much higher velocities and within an extremely brief timeframe (milliseconds), and in more highly concentrated areas on the structure. These factors mean that a resisting structure has far less time in which to respond to the impact.

When subjected to the impact of a ruptured mooring line, an arresting structure's material is accelerated at a high rate at the immediate impact site. The surrounding structure, with its inherent inertia, provides resistance to acceleration. Under the high impact rate, the surrounding material lags the motion of that at the impact site, with it being accelerated solely by the strain force of the material. The high impact nature of these events over a small effective cross-sectional area, results in high stresses, that must be accommodated by the material properties. The short duration of the snapback event results in a high rate of strain on the materials. Often materials subjected to high strain rates exhibit an increase in strength (5-15%) due to the phenomenon known as 'strain rate sensitivity' and show significant reductions in available plastic strain capacity.

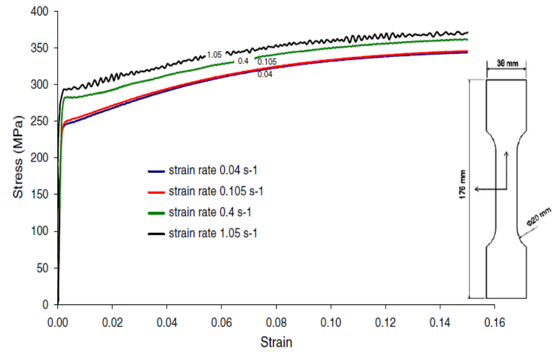

Figure 7: "Stress strain curve with different strain hardening rate" Avril S, Pierron F, Sutton M, Yan J (2008).

The material behaviour effectively 'weakens' the arresting structure when subject to impact conditions. The outcome is a situation where the structure is unable to deform controllably to arrest the impact, leading to penetration or rupture, and emission of dangerous debris.

This can be further demonstrated by a real-world test, which directly compares the impact severities of a car (a large object) to a section of a ruptured mooring line (a much smaller object) and the observed responses of an identical barrier. A 1000 kg car travelling at 150km/hr impacting a barrier at 20 degrees has an impact severity of 101 kJ. When it impacts a barrier that energy is distributed over a large area, enabling the barrier to contain the vehicle. (ref. Figure 8).

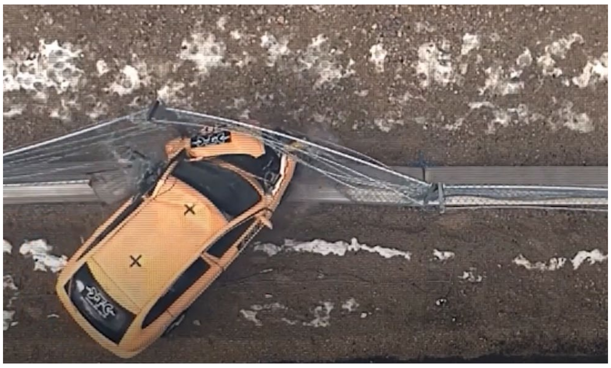

Figure 8: Geobrugg F1 Debris Fence during FIA test, successfully arresting a 1000 kg vehicle @150 km/hr – Geobrugg, (2022)

Comparatively, a mooring line with an assumed impacting section of ~2 m (in the example case the elbow) weighs 5.16 kg. With an impact speed of 648km/hr, the elbow section has an impact severity of 83 kJ. (Note: if the whole tail section is included as the mass, in the example case 7.8 m, the impact severity is then calculated as 325kJ*)* When the section impacts an arresting structure that energy is concentrated in a very small area, enabling penetration of the arresting structure. (ref. Figure 9).

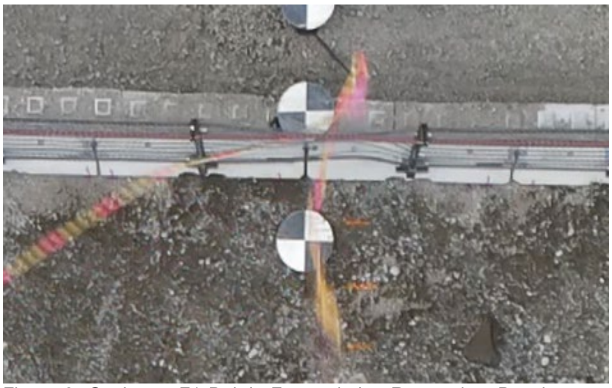

Figure 9: Geobrugg F1 Debris Fence during Research + Development snapback test to establish baseline, unsuccessfully arresting ruptured mooring line - Smith A.S, (2021).

6.1 Distinct loading events

When assessing the impact of a mooring line tail on an arresting structure, it is essential to recognize three distinct loading events (ref. Figure 10 and 11):

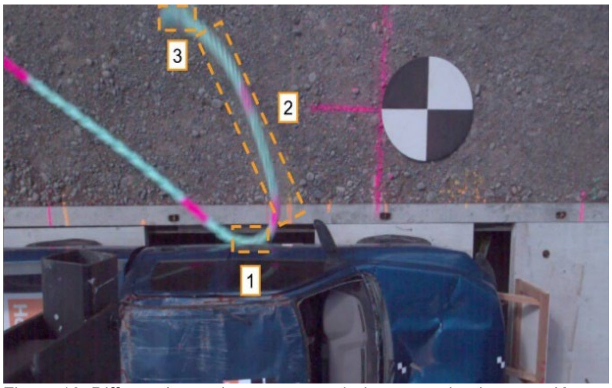

Figure 10: Different impacting segments during a snapback event - Keane R, (2024)

1. Elbow Impact: Initially, the mooring line elbow strikes the arresting structure, covering a length of approximately 300 mm.
2. Tail Impact: Subsequently, the tail of the mooring line exerts sustained loading on the arresting structure, with the specific contact length dependent on length and trajectory of the tail.
3. Tip Impact: Finally, the tip of the mooring line makes contact, covering a length of around 200 mm.

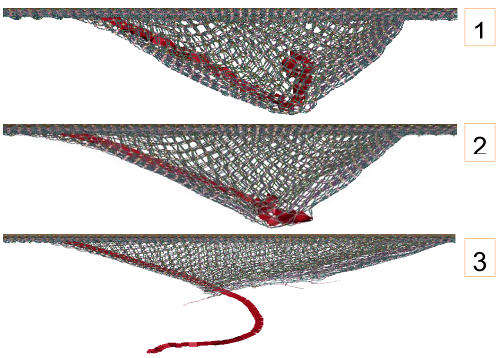

Figure 11: Simulated distinct loading events (1-3) during a snapback event Wong C, (2023)

6.2 Key impact characteristics

These distinct events vary in characteristics such as speed and impact location. Their sequential occurrence and diverse properties can lead to different loading patterns on the arresting structure. The performance of the arresting structure is heavily dependent on variations in these characteristics, specifically:

6.2.1 Velocity of each critical impact event

When a mooring line fails under tension, it behaves like a series of stretched springs suddenly allowed to contract. As the line accelerates (due to force applied by the tension at rupture), its momentum, represented by:

$$p = mv \ (5)$$

Where p = momentum, m =mass, and v = velocity. p remains constant if there is no net external force acting on it (Newton's 2nd law). Considering mass, only the impacting tail section (measured from elbow to tip) matters. In sweeping failures, this section reduces in size as the line unravels like a whip, causing velocity to increase, until impact (conservation of momentum). Even when the elbow impacts the arresting structure, the velocity of the tip may continue to increase. (ref. Figure 12 and 13):

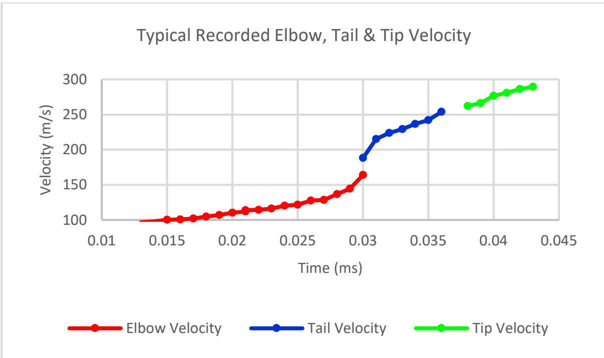

Figure 12: Typical recorded velocities of the elbow, tail and tip during a snapback event with an 85T synthetic mooring line ruptured at 50 tonne - Keane R, (2024)

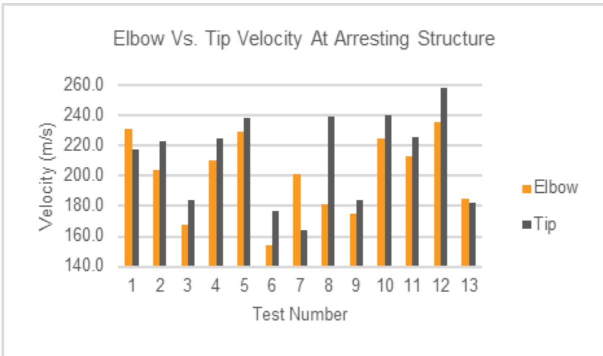

Figure 13: Elbow Vs. Tip velocity results when impacting an arresting structure with an 85T synthetic mooring line ruptured at 50 tonne - Keane R, (2024)

6.2.2 Duration between critical impact events

When struck by a ruptured mooring line, arresting structures face limited reaction time compared to traditional energy-absorbing designs. snapback impacts occur rapidly, causing immediate changes in material states like strain hardening. This quick impact, akin to a speeding bullet, can lead to penetration or rupture of the arresting structure, and release of dangerous debris. The double impact of the elbow followed by the tip further heightens this risk, with shorter durations between events increasing the danger. To expand, under the initial impact from a ruptured mooring line, the impacted material is typically loaded into the plastic region (refer to state 1 in Figure 14). Previously this load was assumed to be applied from a single impact event. Using this assumption, providing the impact load does not exceed the failure strain, a suitably strong material can theoretically recover and relax into the zero-load region, with residual plastic strain (refer to state 2 in Figure 14). However, as previously stated there can be multiple loading events from a single snapback event. In this case, following the first impact of the ruptured mooring line (from the elbow), the material may only have time to unload to state 2 before the secondary impact, meaning that properties of that material is much lower capacity compared to the theoretical capacity.

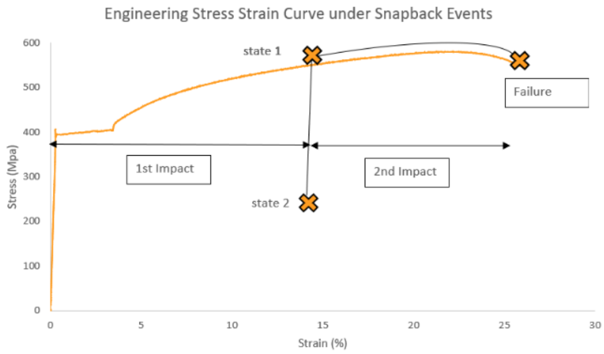

Figure 14: Material response from double impact of a snapback event - Wong C, (2023)

Short tails result in rapid, high-loading impact events of millisecond duration, while longer tails result in more sustained loads as shown in (ref. Figure 15):

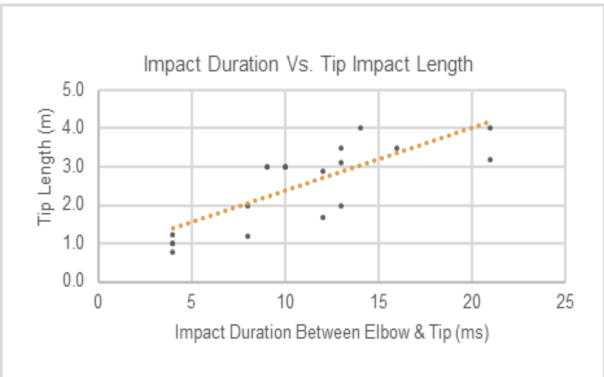

Figure 15: Impact results comparing between Elbow and Tip vs. Tip impact length from an 85T synthetic mooring line ruptured at 50 tonne - Keane R, (2024)

6.2.3 Position of critical impact events

When a mooring line tail collides with an arresting structure, the positioning of each impact event may vary, leading to differing loading points. The overall impact size is a composite of the positions and sizes of all impact events—the elbow, tail and tip. The location of the initial impact (elbow) is determined by previously discussed variables. Conversely, the size and location of the second and third impact events depend on the tail's length and trajectory. A shorter tail leads to the tip impacting closer to the initial impact point. The tip's impact position on the structure may deviate to the left, right, or even overlap with the initial impact location (ref. Figure 16) resulting in a smaller overall impact area and heightened concentrated loads.

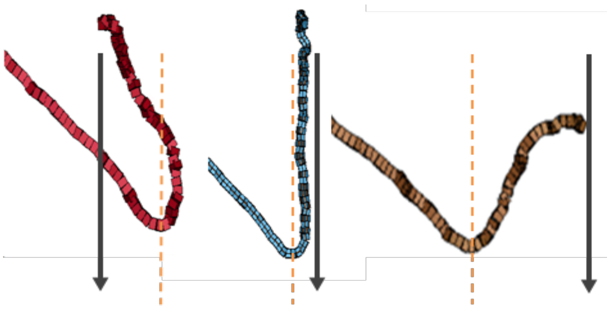

Figure 16: Left tip impact, Centre tip impact (piling) and Right tip impact - Wong C, (2023)

The successive impact events elevate the risk of material failure, as the impacted area is already stressed and damaged from the initial impact and may already be approaching capacity. Particularly, if the second tip impact occurs near the weakened area from the first event, compounded by shorter durations between impact events due to the truncated tail, it increases the likelihood of catastrophic failure (ref. Figure 17):

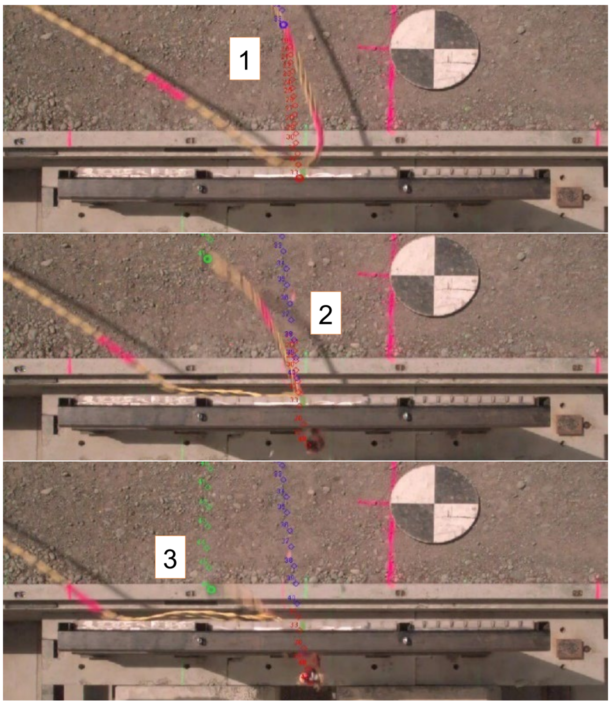

Figure 17: 1. Elbow impact (red track) 2. Tail impact, same location (blue track) & arresting structure penetration 3. Tip impacts to the left (green track) - Keane R, (2024)

7. Conclusion

In conclusion, this study emphasizes the importance of understanding the dynamics of snapback to develop better structures that can handle the risks of high-energy snapback events. Traditional design methods based on static assumptions fall short when dealing with the complex nature of snapback impacts. By using advanced testing and design approaches, like non-linear FEA and full-scale physical tests, we can predict and improve the performance of structures designed to stop snapback. (ref. Figure 18):

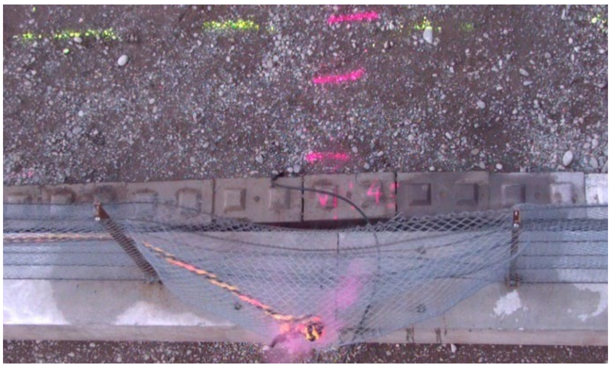

Figure 18: Geobrugg Fixed Foundation Snapback Protection Structure during validation testing, successfully redirecting ruptured mooring line - Smith A, (2021)

This research not only offers a path to safer maritime operations but also calls for the industry to adopt these advanced methods. Moving forward, it's crucial to apply our understanding of snapback in practical ways to protect people and assets at sea. (ref. Figure 19):

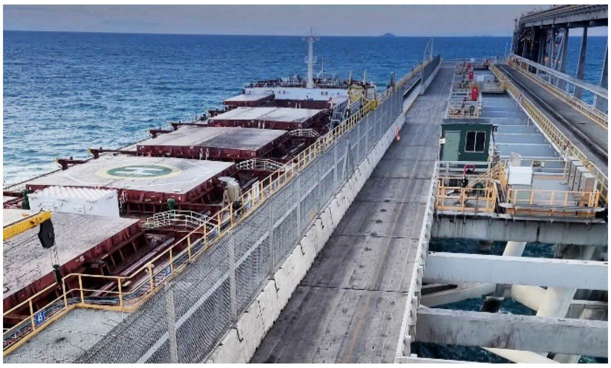

Figure 19: Geobrugg Snapback Free Standing Protection Structure installed at Hay Point coal terminal - BHP Mitsubishi Alliance (BMA), Hay Point Mackay, (2021)

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