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Failure Analysis in Vehicular Crash Reconstruction

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ABSTRACT – *MIROS has been involved in crash investigation and reconstruction since its inception in 2007, and its efforts have provided valuable evidence in improving road safety in Malaysia. In reconstructing a vehicular crash, applying forensic engineering principles is crucial in understanding the cause of failure, especially mechanical and structural failure. This paper discussed several mechanical and structural failures frequently encountered in high-profile cases investigated by MIROS. The cases used in the discussion are obtained from the MIROS Crash Investigation and Reconstruction Database (CIRD). Among the cases highlighted include heavy passenger vehicles with substandard production quality and poor maintenance and road barriers built not according to proper safety protocols. Based on the findings, improvements or interventions made are highlighted. The paper also deliberates on objectives and the means of failure analysis in crash reconstruction.*

KEYWORDS: Road crash, crash reconstruction, forensic engineering, mechanical failure

1. INTRODUCTION

Road traffic crashes and injuries are well-known problems in developing countries like Malaysia. Statistics by the Royal Malaysia Police (RMP) show that the average number of fatalities due to road traffic crashes has been around 6,000 yearly since 1995 (RMP, 2019). With burgeoning deaths, the Malaysian Institute of Road Safety Research (MIROS) was established in 2007 to find new and innovative approaches to tackle road safety issues.

One of the crucial approaches adopted by MIROS from the outset has been the establishment of a comprehensive crash investigation operation (Abidin et al., 2012). This process encompasses the investigation and reconstruction of traffic collisions to identify the causes and contributing factors, whether stemming from human actions, vehicle-related issues, or aspects of the road environment (Kassim et al., 2018). Since 2007, MIROS has investigated over 1,000 crash cases. The insights gained from these investigations have supplied the government with evidence-based solutions to enhance road safety (Jawi et al., 2015).

MIROS' crash investigation and reconstruction team comprises individuals with diverse engineering and science backgrounds. This diversity is essential because road crash analysis is intricate and demands interdisciplinary expertise. Reconstruction applies forensic engineering principles to uncover the causes and contributing factors scientifically. Forensic engineering involves investigating failures, ranging from serviceability to catastrophic events, which may result in civil and criminal legal actions (Neale, 1999). Technology and policies have introduced multiple layers of redundancies for crash prevention and mitigation. Therefore, it is crucial to identify points of failure not only for specific legal redress but also as technical feedback for design improvements.

Figure 1 illustrates that human behavior, in interaction with road and vehicle factors, accounts for 93% of road crashes. These behaviors may manifest as a driver's failure to stay alert at the wheel, disregard for traffic lights, lapses in overtaking maneuvers, and various other instances. While the contribution of road infrastructure and vehicle-related factors is relatively low compared to the human element, failures in the structure, materials, and components can significantly escalate the crisis, leading to more catastrophic outcomes. Therefore, correctly identifying such cases and implementing appropriate measures by road transport authorities could help reduce crashes and casualties on Malaysian roads. This paper showcases examples from MIROS' in-depth crash investigations, highlighting instances where failures in vehicles and road infrastructure have intensified the severity of crashes and occupant injuries.

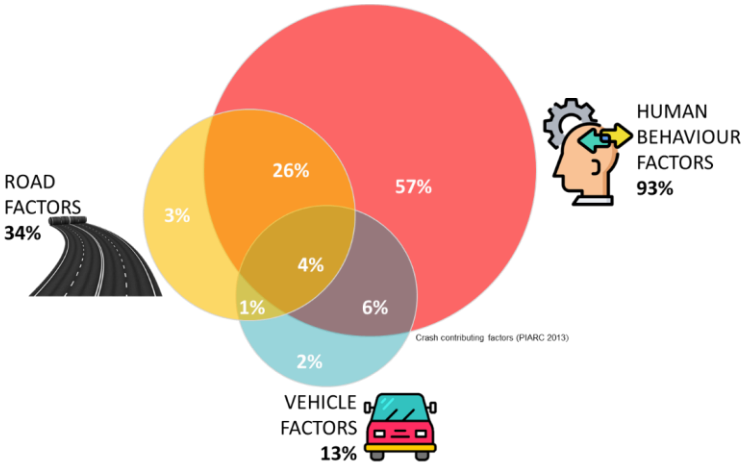

FIGURE 1: Crash contributing factors (PIARC, 2013)

2. METHODOLOGY

The analyzed data for this paper was sourced from MIROS' Crash Investigation and Reconstruction Database (CIRD), which archives all cases handled by MIROS' crash investigation and reconstruction team since 2007 (Abidin et al., 2021). The team's general methodology is illustrated in Figure 2.

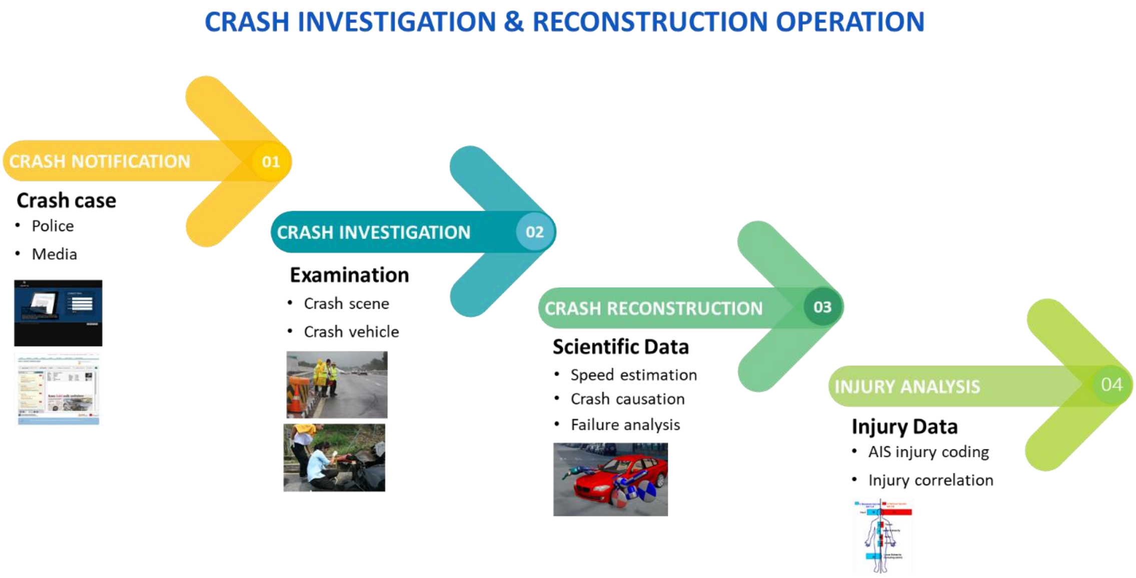

FIGURE 2: MIROS' in-depth crash investigation methodology

Crash investigations were primarily conducted retrospectively within one or two days after the crash, although immediate priority was given to high-profile cases, prompting the team to initiate investigations promptly. Crash analysts were dispatched to the crash site and respective police stations to gather crucial information. At the crash scene, essential evidence, such as vehicle brake and gouge marks, was measured and recorded. Crashed vehicles underwent thorough examination for damage profiling, identification of safety feature performance, assessment of mechanical failures, and detection of pre-crash defects. The dispatched team meticulously photographed all physical evidence during these procedures. Interviews with crash scene witnesses, such as traffic police, were also conducted.

A crash investigation form was used to systematically record all necessary crash data to be analyzed. This form was carefully designed in collaboration with experts from the Birmingham Automotive Safety Center to cover all critical crash information and is especially adapted to the Malaysian context. An extensive amount of data was collected not only for immediate investigation but also for more in-depth analysis in the future. The crash investigation form is mainly divided into three parts: crash scene, vehicle, and human aspects, as per the system components of road safety.

Once relevant data has been collected, the crash reconstruction begins. The primary outcomes of this process include determining the vehicle's speed and position over the timeframe, as well as identifying post-crash, crash, and pre-crash contributing factors. In instances where mechanical failure is observed, forensic engineering applications will be employed to determine the cause of the failure.

There are three primary goals for failure analysis: Firstly, to determine whether a component found to be broken did or did not cause the crash. This aspect often relies heavily on roadway evidence and the application of reconstruction principles. Secondly, to determine the primary cause of an identified failure. In discussing why the effect produced such a result on an identified failure, the forensic scientist or engineer relies heavily on inspections and testing of the suspected parts, the history of the vehicle, and how it was operated. Lastly, the third objective is to determine, for each component or structure found to be broken (cause), whether it did produce the observed injury (effect). This aspect relies on occupant injury information, human contact evidence, and the application of injury biomechanics.

3. RESULTS

The following case studies highlighted examples from real-world crashes where failures occurred in either the vehicle or road infrastructure, resulting in heightened severity of the crash and injuries to the occupants. Three prevalent areas of failure are underscored for future attention.

3.1 Vehicle Structural Integrity Failure

MIROS investigations into Heavy Commercial Passenger Vehicle (HCPV) crashes have revealed widespread mechanical failures of superstructures during collisions, resulting from degraded structural integrity (Hamid et al., 2019). Numerous HCPV superstructures were found to deviate from standard design rules, especially UN Standard R66, with severely compromised strength. These non-conforming and degraded superstructures have led to catastrophic mechanical failures upon impact, exacerbating crash injuries and fatalities.

In a single crash that resulted in six fatalities and 25 injuries, a bus ran off-road and punched through a guardrail, collided with a tree stump, and subsequently overturned. The impact caused the entire roof to collapse and flatten the passenger cabin (Figure 3). Inspection of the bus registration history revealed that the vehicle was already 16 years old, and the structure was found to be severely rusted (Figure 4). Further examination revealed that one of the significant factors contributing to the structural failure was the highly deteriorated roof structure material. The manufacturer welded the pillars together instead of using a continuous ring system (Figures 5 - 7). The welded sections have been determined to be the weakest area, thus serving as the undesired failure modes during the crash.

An in-depth material analysis using a Scanning Electron Microscope (SEM) revealed that the bus superstructure was constructed using cast iron (Figures 8 and 9) instead of high-carbon steel. In this case, it can be suspected that the lower-quality material is used to save manufacturing costs. Additionally, there is no evidence of any rust preventive coating having been applied to the bus structure.

FIGURE 3: Bus roof that collapsed and flattened the passenger cabin

FIGURE 4: Severely rusted structures

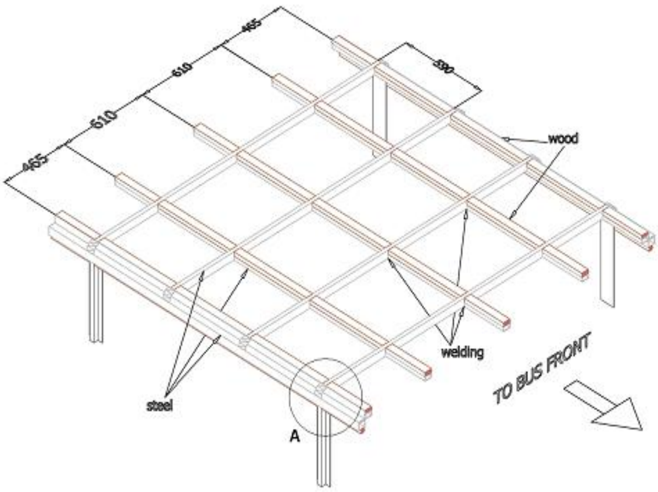

FIGURE 5: The manufacturer simply welded parts together to connect the pillars

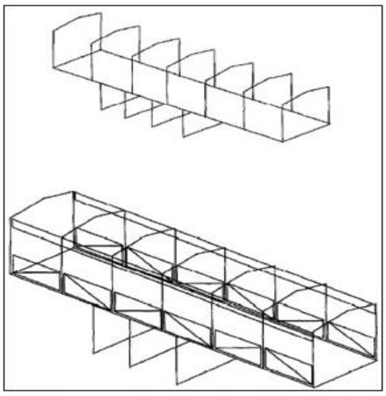

FIGURE 6: Example of a proper continuous ring system

FIGURE 7: Rusted structure at the welded section

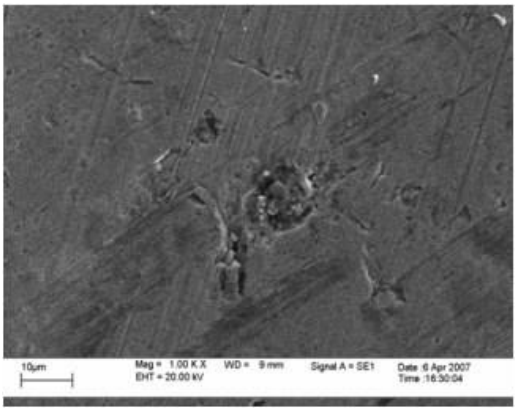

FIGURE 8: SEM image of a sample from the bus superstructure

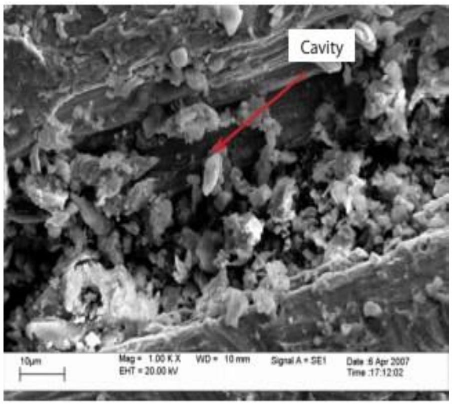

FIGURE 9: Grain structure of sample from the bus superstructure

In a different incident involving a bus, 8 out of 33 occupants died when the bus collided with the rear end of a tanker. The leading cause of the crash was brake failure when the bus was traveling downhill. Furthermore, the inadequate structural integrity of the bus played a role in exacerbating the severity of fatalities and injuries. The steel structure of the bus exhibited significant rusting, and the seat anchorage was identified as notably weak. The coachbuilder used screws and bolts to attach the seats to the bus floor, which consists of plywood with a reinforced wood structure. Figures 10 and 11 show the typical anchorage failures in the bus. Only four seats remained attached to the floor, and even those had gone loose.

FIGURE 10: Improper seat design and anchorage caused seat detachment upon crash

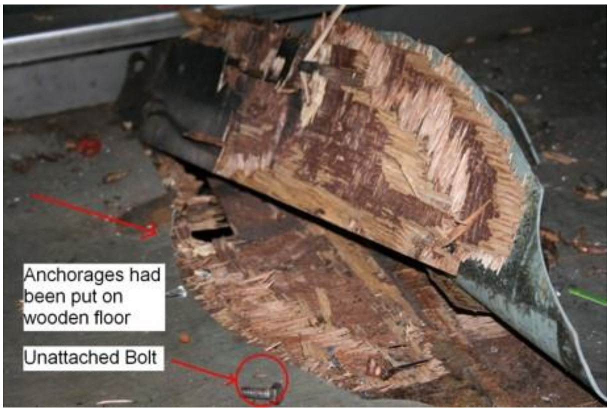

FIGURE 11: Floor made of plywood unable to secure seat anchorage

3.2 Vehicle Component Failure

It is typically uncommon for a vehicle axle to become detached in a crash. However, in a notable crash case examined by MIROS, the front axle of a bus separated upon colliding with a concrete barrier. According to the analysis, the detachment resulted from the failure of high-tensile bolts that connected the axle to the front suspension assembly, as depicted in Figures 12 and 13. The bolts that failed, retrieved from the bus axle and the crash site, underwent examination using a Scanning Electron Microscope (SEM) and Energy Dispersive X-ray (EDX) to ascertain the primary mode of failure, the bolt's base material, and its overall quality.

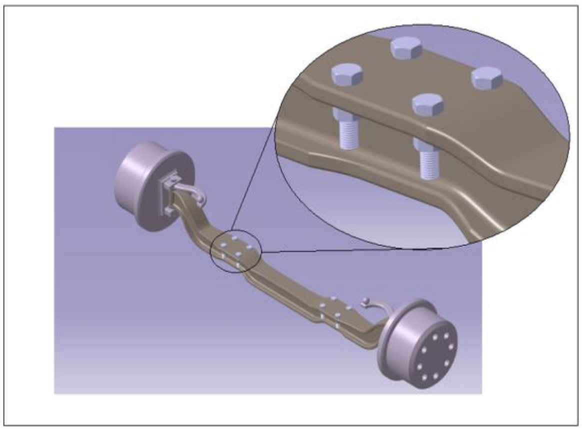

FIGURE 12: Close-up front axle with bolt location

FIGURE 13: Two high tensile bolts for axle connection found at the site

The examination findings reveal that the failure of the axle bolts was a result of multiaxial tensile and shear loads from the impact. The EDX analysis indicated that the bolts had a non-standard material composition, with unusually elevated Carbon (C) contents compared to the standard cast iron composition. Additionally, the presence of voids in the bolts contributed to internal stress concentration on the microstructure, ultimately leading to failure.

A comparative analysis was also conducted using an original bolt obtained from the chassis manufacturer. Upon comparing the results with the failed bolt, it was determined that the crashed bus had replaced the original with substandard, lower-grade axle bolts. The noticeable disparity between the original and the failed bolts underscores an inappropriate choice of fasteners for the axle, a component of paramount importance in a vehicle. The use of substandard components in such critical subsystems should be prohibited, as their failures have the potential to escalate into catastrophic consequences.

3.3 Crash Barrier Failure

Crashes involving crash barrier failure were regularly encountered by MIROS crash investigation (Hamid et al., 2017). In a collision involving the roadside crash barrier or guardrail, the typical failure is the inability of the guardrail to contain an errant vehicle and deflect it back to its normal course. The failure is usually due to substandard design or non-compliance with guardrail installation standards. The typical design issues include adopting lower than required performance or test level, insufficient length-of-need (LON), and unprotected terminal end.

In numerous instances, there was also improper installation of crash barriers, impacting their performance during collisions, notably affecting the designed collapsing mechanism for the barrier system. In the specific case where the bus punched through the guardrail, slid down a slope, and overturned, the inadequate provision of a dynamic deflection zone behind the guardrail was the contributing factor (Figure 14).

FIGURE 14: Inadequate dynamic deflection zone behind the guardrail

The guardrail posts positioned close to an embankment slope lacked the strength required to withstand the impact of the bus. As depicted in Figure 15, a deflecting guardrail is intended to redirect a runaway vehicle back onto the road, enabling the driver to regain control. However, in this particular case, even if the guardrail had been correctly installed, it likely couldn't deflect the bus as it was not designed to contain such large vehicles. The most suitable barrier system for containing heavy vehicles should undergo crash testing to meet Test Level 6 standards.

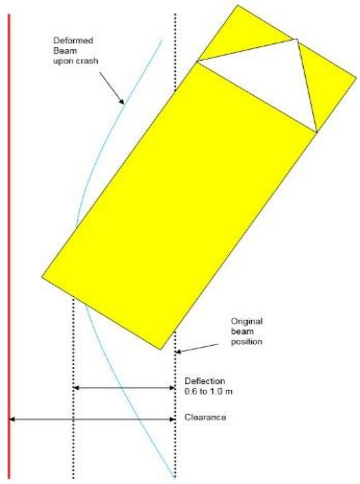

FIGURE 15: A deflected guardrail should divert the run-off vehicle back onto the road

Moreover, inadequate end-treatment of the guardrail presented a threat to the passing vehicles. According to cases investigated by MIROS, the protruding end of the guardrail led to instances where errant vehicles were pierced by the rigid panel, resulting in severe injuries to the occupants (Figure 16). These protruding ends are typically found in the gap section between median guardrails. In another incident, improper end-treatment of a bridge barrier resulted in the bridge railing penetrating the bus's passenger compartment, causing fatal injuries to ten occupants (Figure 17). An examination of the site revealed that the bridge barrier was not installed in compliance with standards. The end treatment of the bridge should have been installed flush and aligned with the concrete barriers to prevent any hazardous protrusions.

FIGURE 16: The protruding end of the guardrail penetrated the car

FIGURE 17: The bridge railing penetrated the bus passenger compartment

In one of the cases investigated by MIROS, the median concrete barrier failed upon impact by a bus. Instead of effectively preventing the bus from crossing into the opposite lane, the barrier shattered into pieces (Figure 18). The site investigation revealed that the barrier adhered to the dimensions of the Test Level (TL) 5 New Jersey Concrete Barrier (NJB) but lacked the necessary reinforcement bars. While concrete is a material highly resistant to compression forces, it is weaker against tensile forces. By incorporating steel rebars, a material with high tensile strength, into the concrete, the structure would have exhibited robust resistance against both compression and direct tensile actions. Strengthening the concrete barrier in this way would have prevented it from easily breaking apart and effectively halted the bus from penetrating through into the opposite lane.

FIGURE 18: The barrier was broken into pieces from the impact and failed to stop the bus from launching into the opposite lane

4. DISCUSSION

The compiled MIROS case studies reveal that none of the mechanical or structural failures directly caused the crashes but rather exacerbated the crash outcomes. The severity of these outcomes might have been diminished, if not entirely prevented, had the systems, components, or structures performed as expected without failing during the crashes. Although these mechanical and structural failures are relatively infrequent, their consequences are often catastrophic.

Failures of components are often linked to the use of substandard components and can also result from inappropriate modifications to the vehicle. Therefore, there should be proactive monitoring of vehicle modifications by authorized bodies. The use of substandard components should be strictly prohibited due to their unreliable performance and questionable integrity when exposed to operational stresses. According to Van Schoor et al. (2001), tires and brakes stand out as the two most significant components contributing to catastrophic mechanical defects.

Apart from vehicular factors, such as critical structural or component failure, deficiencies in road systems and infrastructure also contribute to traffic accidents. The highlighted case above involves the failure of a crash barrier due to the inappropriate application of safety standards. The incident revealed that the contractor responsible for the installation hastily upgraded the guardrails to a higher standard, at least to Test Level 3 (TL3) along existing Malaysian highways and expressways, without conducting a proper risk assessment beforehand. By neglecting various risk factors that vary across different locations along the entire road network, the responsible party failed to establish a safe and compliant roadway environment that meets both local and international safety requirements. The specific area in question is considered high-risk due to the construction of the roadway on a slope cutting through hills with varying contours and gradients, as depicted in Figure 14. In such a high-risk area, TL3 may not be sufficient to prevent heavy vehicles, such as buses and trucks, from encroaching onto the slope embankment. Barriers higher than TL3 must be installed to accommodate heavy vehicles in these situations (REAM, 2006). Other potential inadequacies in road systems that could contribute to potential traffic collisions include faulty installations and the use of substandard infrastructure equipment, such as the installation of the New Jersey Concrete Barrier (NJB) without reinforcement bars.

In the context of the first objective for crash reconstruction, determining whether component failure caused the crash, the case of the detached axle shown in Figures 12 and 13 reveals that the front axle of the bus came off and separated from the bus ladder frame upon impact, not before the collision with the concrete barrier. Road evidence, such as visible skid marks within the crash radius, should be regarded as primary evidence. Skid marks play a crucial role in vehicular accident investigations, as their characteristics and types enable forensic scientists and engineers to accurately determine the pre-crash and post-crash condition of the involved vehicle through trace evidence analysis. Upon a thorough examination of the bus collision in the case study, the skid marks on the roadway provided clear evidence that the front wheels were still attached to the vehicle before impact. This alignment corresponds to the tire skid marks on the roadway leading into the median concrete barrier. Based on these observed pieces of evidence, it can be concluded that the front wheel axle must have detached upon impact and not before. If the front axle had separated from the bus before impact, the skid marks would have exhibited rougher characteristics, including metal grazing and deep pavement scarring on the road surface, as the bus slid forward on its metal frame.

Regarding the second objective of crash reconstruction, which involves determining the primary cause of an identified failure, the examination of the axle that separated from the bus revealed that the detachment occurred because the bolts and fasteners, serving as anchorage points between the wheel axle and the main chassis, failed to withstand the excessive impact force during a crash. Material tests conducted on both the failed and original bolts indicated that substandard lower-grade axle bolts had been substituted for the higher-performing originals.

As for the third objective, to determine, for each component or structure found to be broken (cause), whether it did produce the observed injury (effect), we can take the example of the bus cabin structural failure, which resulted in the complete collapse of the roof assembly. Evidence at the crash scene showed many occupants had been trapped under the roof, and the injury details confirmed that a high number of the occupants had suffered crushing injuries. Had the superstructure persisted and withstood the crushing impact, the bus occupants would have had higher chances of survivability. A properly designed superstructure should be safe even if it is put under excessive stress. It should be able to support its weight while enduring external forces that could lead to deformation, breaking, and catastrophic failures of the structure under duress. As a result, the occupants would be protected within this “survival space”, especially during rollovers. Thus, passengers are less likely to be fatally crushed by the roof.

5. CONCLUSION

The failures emphasized in these case studies can stem from various modifiers and attributes, which are not consistent across individual cases. These factors encompass faulty installation, inadequate maintenance, excessive modifications, and non-compliance with regulations. Through forensic engineering principles, investigations into mechanical and structural failures can be conducted to comprehend the factors leading to their failure. While these failures may not always be the direct cause of accidents, they often result in more severe damage and injuries. Identifying these points of failure enables the implementation of measures to mitigate them, such as a more robust redesign, the incorporation of additional buffering layers for safety redundancies in technical systems and regulations, or the enforcement of stricter policies.

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