Paper

Learning from failures

J. C. Chapman,
FREng, FCGI, BSc, PhD, FIStructE, FICE, FRINA
Chapman Associates / Imperial College of Science, Technology & Medicine

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Synopsis

The paper discusses 15 failures within the writer's experience, from which useful lessons can be drawn. Deaths or serious injury resulted in about half the events described. In some instances, the cause could be clearly established, and steps were taken to modify existing practice, perhaps because they came to public attention. The accidents and causes were all different in character. The paper concludes with a list of lessons perceived by the writer. It is suggested that a databank of accidents and near misses should be created; this could make a major contribution to safety and would enable the frequency of occurrence of types of accident and their causes to be assessed.

Introduction

The transmission of experience is a basic and important function of a professional engineering Institution, and is therefore an obligation on the membership. The aim of this paper is to contribute to the collective experience of failures and thence to the promotion of safety. 'Failure' is not intended to connote 'collapse', but sometimes causes collapse.

There are organisations dedicated specifically to safety, such as the Standing Committee on Structural Safety, the Health & Safety Executive, and the Technical Council on Forensic Engineering of the ASCE, which publishes *Journal of Performance of Constructed Facilities*. There are also numerous published papers, and a remarkable book[1]. The Building Research Establishment is compiling a databank on defects in buildings. This paper does not attempt to review those or other sources of information; that, with a reporting system for incidents, might be undertaken on behalf of industry by CIRIA. The aim would be to create a 'safety bank' or, more ambitiously, a 'performance bank'.

This paper aims only to describe some events within the writer's experience and to draw some lessons from those events, as a small contribution to what should be an available body of experience. The writer does not purport to be expert in the design of the structures or components that failed; neither does he seek to judge individuals who made mistakes: we all do that. He writes as the investigator, who had the incomparable benefit of hindsight.

What may seem to be a disproportionate number of these events occurred in a marine environment, probably because such structures are exposed to severe, highly variable and repetitive loading and because the ocean is unforgiving of operational error or misjudgment. Also, marine structures usually require contributions from several interacting disciplines, and engineering management becomes especially important. However, the lessons can have wider application. Lifting structures, for example, has some comparable attributes.

Some failures were the subject of detailed investigation and reporting; others were incidents where remedial steps were taken and reporting was not required. The criterion for inclusion is that the incident should contribute to the body of experience. A minor failure, which caused no injury, might be so rare that no action is required beyond remedying its effects. But rarity or frequency can be established only if failures are reported, regardless of the severity of the consequences of the failure. Near misses can be significant and should be reported and acted upon. This is recognised, for example, in the aircraft and airline industries.

Risk assessment

A distinction should be made between 'risk assessment' and 'risk analysis'. 'Assessment' is taken here to mean the recognition of particular risks and a statement of steps taken (if any) to mitigate their effects. In some circumstances, the aim might be to prevent injury, but to accept damage or failure. In some countries the normal provision against earthquakes might not extend beyond that which is required to resist wind forces, but in nuclear installations, for example, even the possibility of small tremors will need to be taken into account.

Assessment is assumed to be qualitative in respect of the degree of risk and the consequences of failure. Provision against progressive collapse, for example, is 'qualitative' in the sense that a qualitative judgment is made in arriving at the extent of the damage that a structure is required to survive and also because the cause of the damage does not need to be specified.

Specified causes could include environmental or other loading beyond the assumed limits, accidental loading through collision or operational error, poor maintenance, faulty material, deficient construction, design error, fire. The risks considered should be identified and the preventive measures stated; the consequences of failure will be taken into account. The consequences may be only economic; if the consequences include serious injury or loss of life, economic consequences will always follow. Safety measures are justified economically as well as morally.

In some instances, the risk might be small enough, or protection costly enough, for no steps to be taken, in which case that will be stated. Even though a risk is apparent, and the event is likely to happen at some time, the public perception may be that the risk is acceptable: e. g. it is possible that, on some future occasion, a plane will crash on a train at Gatwick Airport, but the train passengers apparently accept the risk with equanimity, perhaps (if they even think about it) because their risk is less than that of the plane passengers. Road accidents are seen as inevitable and acceptable; officials and ministers are not charged under the Health & Safety Act, which requires all 'reasonably practicable' steps to be taken to ensure safety, because they specify unnecessarily high speed limits, knowing that a reduction, which would be both reasonable and practicable, would reduce accidents whilst saving energy, reducing pollution, and increasing traffic flow. However, static structures not affected by extreme, uncontrollable events are expected to be safe. If unprovoked failure occurs, the public will not be sympathetic to an explanation that this was an exceedingly rare event and that the probability of its occurrence was far less than that of a list of other misfortunes.

'Risk analysis'[2] is taken to mean that the probability of occurrence has been quantified on the basis of past experience. 'Past' may refer to a long period, as for natural phenomena, or to the more recent past, as for tests to determine the variability of material properties or the reliability of equipment. The analysis can then be extended to calculate the probability of a number of independent risks occurring simultaneously. Such calculations provide a rationale for design assumptions and have been standard practice in several industries for many years.

The human factor is especially difficult to assess, but for certain operations data are available, or, given an efficient reporting system, could be obtained. However, equipment design and human performance are interlinked, as are a variety of other circumstances affecting human perform-

Fig 1. Ronan Point

ance. The process of risk analysis, following an open-minded assessment, will highlight factors requiring special attention or indicate a need to duplicate equipment or operators. It seems that design assumptions made regarding risk, such as the reduction in total floor loading for tall buildings, or that certain maintenance operations will be carried out, should be communicated to the owner and operator, for their protection and for the protection of the public, the designer, and the constructor.

A key feature of mandatory risk assessment is that the designer is obliged to consider possible events and effects, however unlikely, beyond the confines of specified loading. The mental approach is different. Appendix A lists a number of eventualities which, it is suggested, should be included in a risk assessment for ship-to-shore structures[3].

The reader may wish to reflect upon the extent to which the risk of occurrence of each of the following incidents would have been reduced if a formal risk assessment had been undertaken.

Ship's derrick

The boom was attached to the mast by a hinge and swivel. Vertical movement was allowed by a hinge consisting of a pin passing through three lugs, one of which was between the other two and attached to the boom. The outer lugs were supported on a horizontal plate which could swivel about a vertical pin passing through a horizontal platform attached to the mast. Lubrication of all moving surfaces was obviously vital, especially at the swivel, but apparently the crew found it more convenient to heave on the end of the boom to free the rusted surfaces. They did this once too often, and the falling boom struck the head of a Polish seaman, who suffered permanent, incapacitating brain damage.

Through the untiring persistence of a Polish resident, the unfortunate seaman was eventually awarded a large sum as compensation, 6 years after the accident. That was the writer's first experience of the legal process and its capacity for delay; perhaps it was thought that the victim might not survive the duration of the process.

(1) Operational error or abuse should be addressed in the risk assessment, and the operational requirements should be placed on record and conveyed to the user.
(2) The maintenance requirements should be clearly stated or referred to in the operating manual.
(3) It is essential that the operator ensures implementation of the operating requirements.

Ronan Point

The cause and nature of collapse was fully reported[4], but is worth revisiting. Ronan Point was a 22-storey block of flats, constructed from precast wall and floor units. A gas explosion occurred on the 18th floor early one morning, and, because the connection between walls and floors failed, the corner wall units peeled away from the slabs. The slabs were then supported only on two adjacent sides (Fig 1), and falling slabs contributed to the failure of slabs below. The number of people killed was remarkably small.

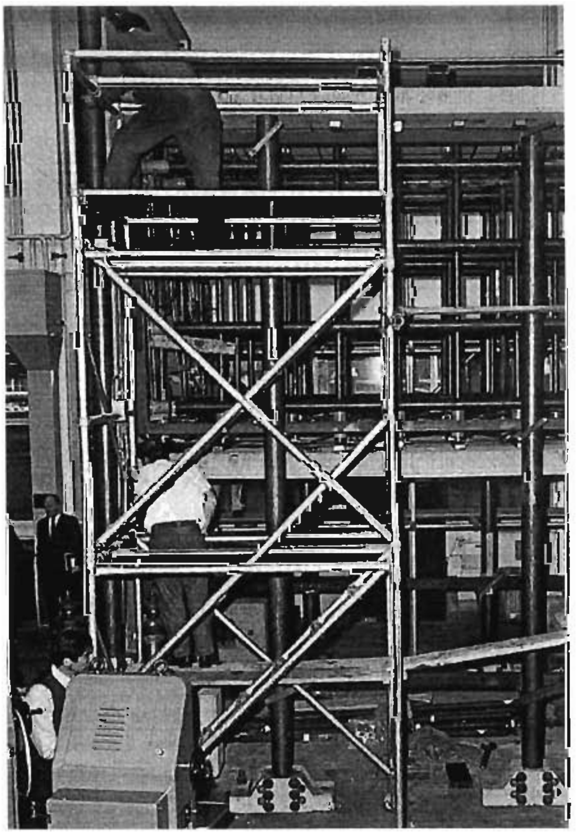
Tests demonstrated that the connection was adequate to resist wind suction, for which the building had been designed (Fig 2).

Some important observations are:
(1) The connection detail was illustrated before the accident in a paper to a conference on industrialised building at the Institution of Structural Engineers[5]. According to the record, the detail caused no adverse comment.
(2) The regulations at that time did not require the effect of explosions to be considered in design.
(3) Gas explosions were not uncommon; for the 10 years preceding the collapse, the average number of explosions p.a. in the UK causing structural damage was 406.
(3) If the question 'should gas explosions in a tall building be considered in design?' had been asked of an engineer or a lay person, the answer would almost certainly have been 'yes'. Apparently, the question was never asked.
(4) A prime duty of an engineer is to ask questions; that is also the essence of risk assessment. If risk assessment had been mandatory at the time, would the vital question have been asked? At least, the question would have had a better chance of being asked.

The connections lacked the strength and ductility that could have resisted the explosion for a sufficient time to enable venting to occur through the double glazing of the windows. Also, they were unable to prevent the progressive collapse which occurred as a result of the local failure.

The accident illustrates the mindset that can occur when designers are attuned to following regulations. It is even perhaps arguable that the accident might not have occurred if there had been no regulations. It is not suggested that regulations are unnecessary, but the design

Fig 2. Ronan Point investigation



process must be such that regulations are not allowed to inhibit the imagination. An excellent study of the frequency and severity of explosions from all causes (except high explosives) is given by Ellis & Currie[7].
(5) As a result of the failure and collapse, the regulations were promptly modified to take account of explosions and progressive collapse.
(6) Provision against internal pressure and progressive collapse does ensure that the components have a certain degree of connection beyond that which is required to resist normal factored loading, i. e. a degree of robustness.
(7) The collapse also stimulated provision for robustness in buildings without piped gas.

Deck failure

A tanker was proceeding under pilot's control up an estuary with a navigation channel that was maintained by dredging. The crew noticed a buckle which spread across the deck and down the ship's side. The amplitude of the deck buckle was about 600mm (Fig 3), and the plating had separated from the stiffeners. The failure was caused by the ship momentarily touching bottom, but the deceleration that must have occurred was so slight that it had not been felt by the crew. The buckling of the ship's side caused oil spillage and pollution along the shores of the estuary. When the ship entered dry dock, local scuffing of the bottom shell confirmed that the ship had touched bottom.

The deck was stiffened by bulb flats attached by intermittent welding. It appeared that torsional buckling (tripping) had occurred, and because the weld was insufficient to resist the transverse moment capacity of the stiffener web, the weld had failed and the plating was then unrestrained by the stiffeners. The connection had been adequate for normal loading but insufficient for the accidental (though not uncommon) loading that occurred.
(1) It would be prudent, where exceptional loadings are possible and where the consequences of failure are severe, to design the weld to resist the fully plastic transverse moment capacity of the web.
(2) More generally, resistance to abnormal events will be greatly enhanced if the connections maintain the integrity of the components.

Delayed fracture

The structures laboratory at Imperial College has a prestressed floor 1m thick. The columns for loading frames are solid circular sections 150mm in diameter; the level of the beams is adjusted by means of grippers which can be moved up or down the columns. The gripper bolts are tensioned hydraulically. Higher grade, high tensile bolts were installed at a presumably safe tension after confirmatory tensile testing. After periods that varied from days to weeks, some bolts fired themselves across the laboratory at lethal velocity.

Expert opinion was that the delayed fracture was caused by hydrogen embrittlement and that the solution was to bake the bolts at a certain temperature; this, it was suggested, would expel the hydrogen. When this was found to be ineffective, the bolt holes were enlarged and lower grade bolts were used. Presumably, the phenomenon of delayed fracture is now better understood, though more recently a manufacturer's assurance regarding bolts of the highest grade was less than absolute. Feedback of user experience would be useful.
(1) It is important to recognise that normal tensile testing does not guard against delayed fracture.
(2) When using higher grade steel, delayed fracture should be considered in the risk assessment.

Early fatigue

A class of six container ships, 227m long, which entered service in 1969, developed fatigue cracks at the ends of hatch side-girders which were detected after the first voyage[8]. The cracks developed further in subsequent voyages

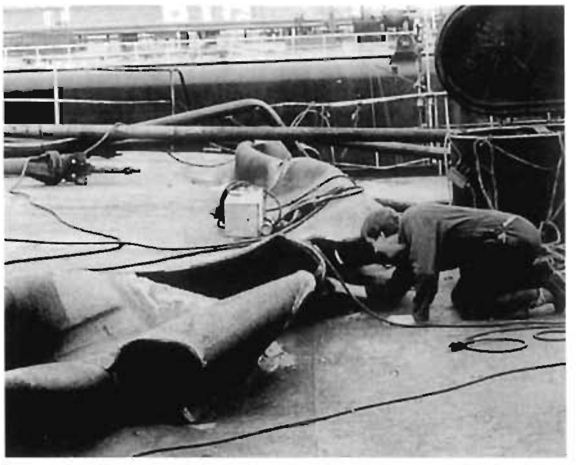


Fig 3. Failure of ship's deck

(Fig 4) but had not extended into the deck plate. The cracking occurred at a discontinuity between hatch girders (curtailment assisted access) and was also attributed to the bow flare, which dispersed the bow wave (the design speed was 22knots) and protected the on-deck containers, but increased the hull bending moment.

A rather radical solution was suggested which was accepted and implemented. The hatch girders were made continuous (so the crew had to climb over) and the ship's sides were continued upwards to a wide bracketed flange which reduced the hull bending stress, increased the stiffness, and enabled additional containers to be carried, with access below. No further cracking occurred.

The lessons were incorporated in the next five ships, 290m long, design speed 26knots, and with deck strips beside the hatches only 2.78m wide. The beam was 32.26m, the maximum permitted by the Panama Canal. To reduce the torsional deformation and increase the torsional resistance, the machinery space was located so that it divided the length of the open section (Fig 5). Measurements were made on scale models of the previous and of the new ships, and stillwater torsion experiments were conducted on one of the previous ships. Also, strain measuring/counting gauges were fitted to the previous ships, to provide data for fatigue assessment. Half-scale models of the deck in the vicinity of a hatch corner were tested in fatigue, and a device to reduce the stress concentration at the ends of the deckhouse was designed, tested, and introduced.

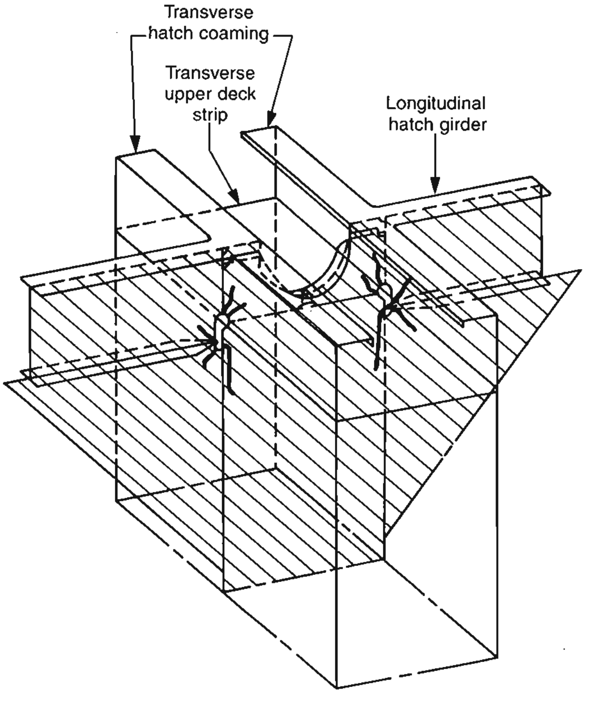


Fig 4. Fatigue cracks in 213m-long container ship

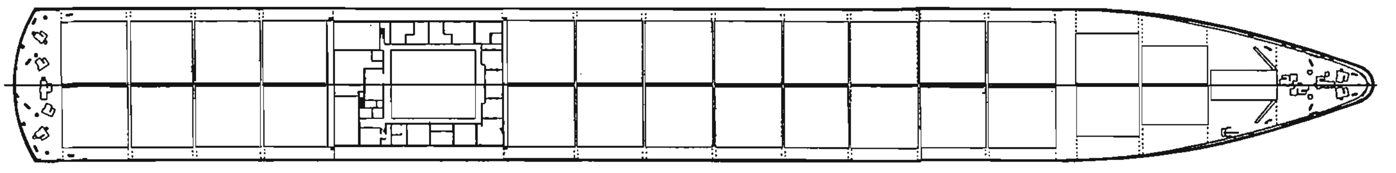


Fig 5. Plan of 274m-long container ship

For the first time, strain gauges were fitted that could be read on the bridge as an aid to safe operation; if a certain strain limit were reached, the master would reduce speed or change course. The facility provided comfort for all concerned and, after some time, when the precaution was found to be unnecessary, the practice was discontinued. The owners displayed an exemplary sense of responsibility in design, procurement, and operation. The relations between owner, builder, and classification society, were cooperative and cordial.

(1) Where the loading, or the structural response, is uncertain, measurement of response in service can be prudent and justified. Instrumentation in dams has been usual for many years.

(2) Cooperation between owner, designer, builder, and operator, is conducive to safe and efficient operation.

Very early fatigue

Whilst piles were being driven through the pile guides of a small accommodation jacket in the southern North Sea, a number of the welded attachments of the cathodic protection anodes failed, and many others were found to be cracked. The jacket was lifted and taken ashore for repair.

The jacket had sloping legs, and the piles were to be driven by a guided steam hammer. In the event, that hammer could not be used to its full capacity because one of the two steam hoses was damaged, so the contractor elected to use a much heavier hydraulic hammer which was not guided, so the blows were applied eccentrically. This resulted in violent vibrations of the jacket, which applied large transverse accelerations to the anode attachments. 80% of the anodes were damaged, and several fell off. It was reported that the pile follower had a permanent deflection of 1/80 of its length and the driven end was eccentrically belled. Marine pile-driving is usually subject to the exigencies of the weather, which makes construction planning and execution especially onerous.

(1) Installation stresses can be important.

(2) The designer needs to be aware of the proposed construction method, and should be notified of any change.

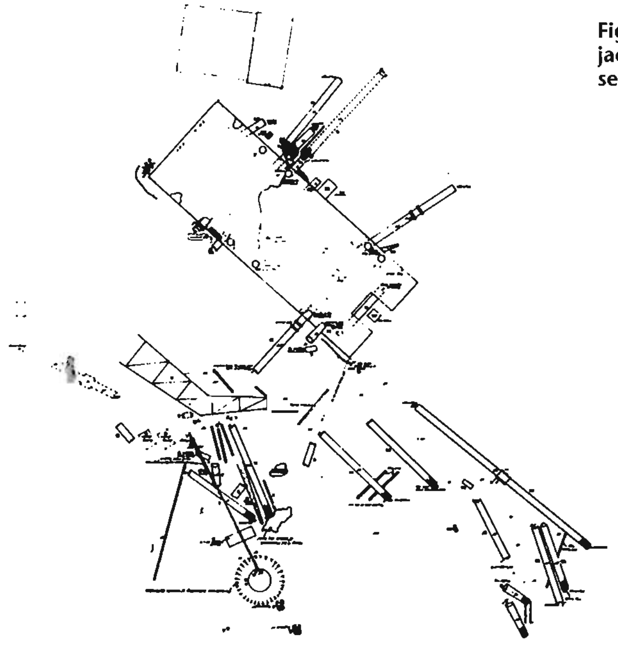


Fig 6. Remains of jack-up barge on seabed

Jack-up barge

Sea Gem was a jack-up barge employed on drilling in the southern North Sea. The barge was moved up and down the tubular legs by a system of vertical jacks and pneumatic grippers above and below the jacks. The barge was suspended by tie bars consisting of flat bars with T-shaped ends.

Whilst the barge was being lowered, prior to changing location, a jam occurred between the legs and the wells through which the legs passed with a small clearance. When the jam cleared, the barge dropped a short distance, fracturing the T-bars on one side of the barge. The barge fell sideways and capsized. Many lives were lost, and a public inquiry followed.

A seabed survey revealed that the legs were broken into many pieces (Fig 6) and were evidently brittle at the prevailing temperature. The radii at the T ends of the tie bars were small and roughly flame-cut. In some cases, the legs had torn through the plating between the well and the side of the barge. The legs had a history of modification, and there were several parties to the construction, ownership and operation of the barge.

There was a presumption that, when the barge dropped, the legs broke and caused the collapse. A further presumption was that, if the legs had not broken, jamming would have prevented a further fall. It had not been noticed that, if the drop on one side was followed by sidesway, the sway would not be arrested (by secondary jamming) until the sway was such that the leg moments would cause ductile failure, or alternatively the well sides would fail.

A scale model (with ductile legs) was made and taken to the court room, where it was demonstrated that sidesway following tie bar failure caused failure of ductile legs, so the collapse could not be attributed to the brittleness of the legs (Fig 7). This had major contractual implications, but, more importantly, it revealed a feature of the design that would need to be taken into account in a risk assessment.

Was the accident caused by design, manufacture, operation, or engineering management? The answer must be 'all four'. The operation did not happen as the designer presumably envisaged, but consistent perfection in operation should not be assumed, and the jam-drop sequence was foreseeable. It would appear that the material specification and the quality of supervision and inspection were inadequate.

(1) Mobile structures, with several suppliers and previous operators, require an especially high standard of risk assessment, inspection, and operation.

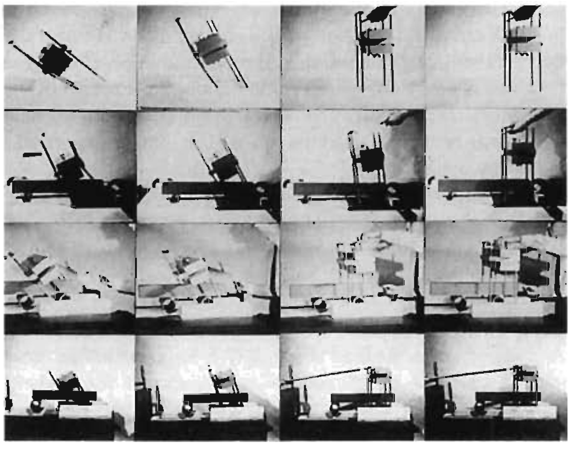


Fig 7. Model of jack-up barge demonstrating mode of failure

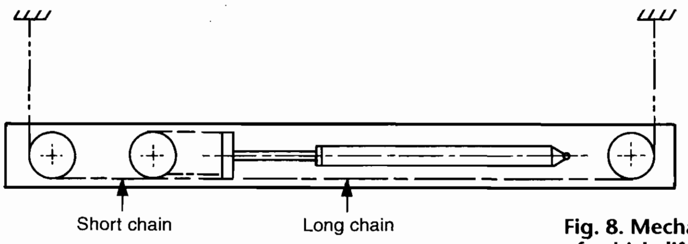


Fig. 8. Mechanism of vehicle lift

(2) Possible departures from the intended mode of operation should be considered in the risk assessment.
(3) The operator should contribute to the design and performance specification, and cooperation should continue through design and construction.
(4) The mechanical, electrical, and structural system should be considered as a whole, probably by a designated system engineer.
(5) The possibility of a mechanism developing should be considered.

Fire brigade ladder

Ladders mounted on fire-fighting vehicles are routinely tested by extending the ladder horizontally. On one occasion the ladder dropped to the ground, causing no injury. The ladder seemed to be an excellent piece of machinery, embodying much engineering skill and experience, but the welded steel lattice frame, through which the ladder was attached to the vehicle, was designed without proper regard to the transmission of the applied forces. Strain measurements confirmed the inadequacy. Although advanced fatigue cracking had occurred, this had not been noticed during routine inspection, because the lattice frame was encased.
(1) Load testing alone does not ensure safety; it should be accompanied by examination of the structure, preferably whilst the test load is applied, because cracks are then more visible.
(2) Access for inspection is essential.
(3) Engineers should have enough knowledge of other disciplines to recognise when advice is needed.
(4) The system should be considered as a whole.

Vehicle lift

The purpose of the lift was to raise vehicles from a covered deck to the weather deck of a ship. In the lowered position, a vehicle was driven up a ramp to the lift platform. In the raised position the platform acted as a hatch cover. The lift was designed to lift a vehicle weighing 45t. The platform, which was 19m long and weighed 33t, was raised and lowered by four chains, which were similar in principle to a bicycle chain. Each had a specified breaking strength of 170t, so their nominal strength factor was large and the platform structure also was conservatively designed.

Three people were riding on the platform for inspection purposes when the platform dropped: one was killed and two were seriously injured. When carrying a 45t vehicle, the nominal force in each chain would have been about 20t; failure occurred when the nominal force was about 8t.

The chains were attached to the weather deck and passed round sprocket wheels at the corners at the platform to a single hydraulic ram on each side of the platform. Two chains turned through 90° around one sprocket wheel and the other chains turned 90° around one sprocket wheel and 180° around an auxiliary sprocket wheel (Fig 8). Therefore, each jack applied tension to two chains of different lengths (8m and 23m). The chains were attached by 65mm diameter bolts to each end of a crosshead at the end of the piston rod. The two cylinders, which were 7m long, were hydraulically connected, so the pressures were equal. To ensure that the two sides of the platform would have the same vertical displacement, the sprocket wheels at one end of the platform were connected by a shaft, the torque in which enabled the tensions in the vertical chains on each side at one end of the platform to be different.

The chain tensions were different for the following reasons:
(1) The long chain had more friction, because it turned through 270° whereas the short chain turned through 90°.
(2) The long chain extended more than the short chain, so (if the slack were removed) the corners supported by the short chains would lift off the deck before the other corners. A similar situation existed on arrival at the upper deck.
(3) The centre of gravity of a vehicle would normally not be midway between chains, either longitudinally or transversely.
(4) Although, in principle, adjustable bolts enabled the short chain slack to be increased to compensate for relative chain extension, this was difficult to achieve, even for a particular concentric loading.

Thus the tensions in the chains on each side of the platform would differ, and so would the tensions in the two chains attached to a piston rod crosshead. The crosshead was rigidly attached to the piston rod and the chains were attached to the crosshead by M60 eye bolts at 0.5m centres. Unequal bending moments were therefore applied to each side of the crosshead and to the piston rod, which, according to the evidence, bent visibly under load. When the platform was in the raised position, it was supported on retractable pawls.

The piston rod was connected to the crosshead by screwing the threaded end of the piston rod into the crosshead. The rod was reduced in diameter at the threaded end, with a 2mm radius at the reduction. For nominally equal chain forces, the axial stress in the reduced end would have been $50N/mm^2$. The stress concentration factor would have increased this to about $130N/mm^2$. The oil pressure relief valve would have limited the axial stress to about $85N/mm^2$. So, if only axial stress were considered, the highest stress that might have been envisaged would have been 40% of the specified minimum yield stress, $550N/mm^2$ (though subsequent investigation found that the yield stress was about half that). However, calculation of the stresses that could have occurred as a result of the various effects causing unequal chain forces showed that the bending stress could have been several times the nominal axial stress. That was the cause of the fatigue failure.

A surviving witness said that, when failure occurred, there was a loud bang, followed immediately by a second bang. Subsequent investigation showed that the port side piston rod had a deeper fatigue crack than the starboard side rod, so presumably the port side rod failed first. The long chain and the horizontal part of the short chain would have immediately lost tension, but the vertical part of the short chain would momentarily have retained tension by virtue of the sprocket wheel which was connected to the starboard sprocket wheel. The vertical part of the starboard short chain would have lost tension because the diagonally opposite corner was then unsupported and the starboard piston rod was then supporting the whole weight of the platform through the other two diagonally opposite corners, so the starboard rod would then have failed. There were guide columns on one side of the platform, but arrestors were not provided.

It transpired that, a few months previously, piston rod failures had occurred on another ship. This prompted a recommendation that the detail should be inspected periodically: in the event that visual inspection revealed an irregularity, penetrant dye would be applied and, if that confirmed cracking, a rod of new design would be requested. The logic was flawed, and the lack of urgency astonishing. It is also surprising that the operators were not alerted to danger by the nature of the recommendation. Where force transfer from cracked to uncracked components is not possible, fatigue cracks develop rapidly, and periodic inspection cannot ensure safety.

The numerous drawings suggest care and competence. The designers displayed caution in respect of those crite-

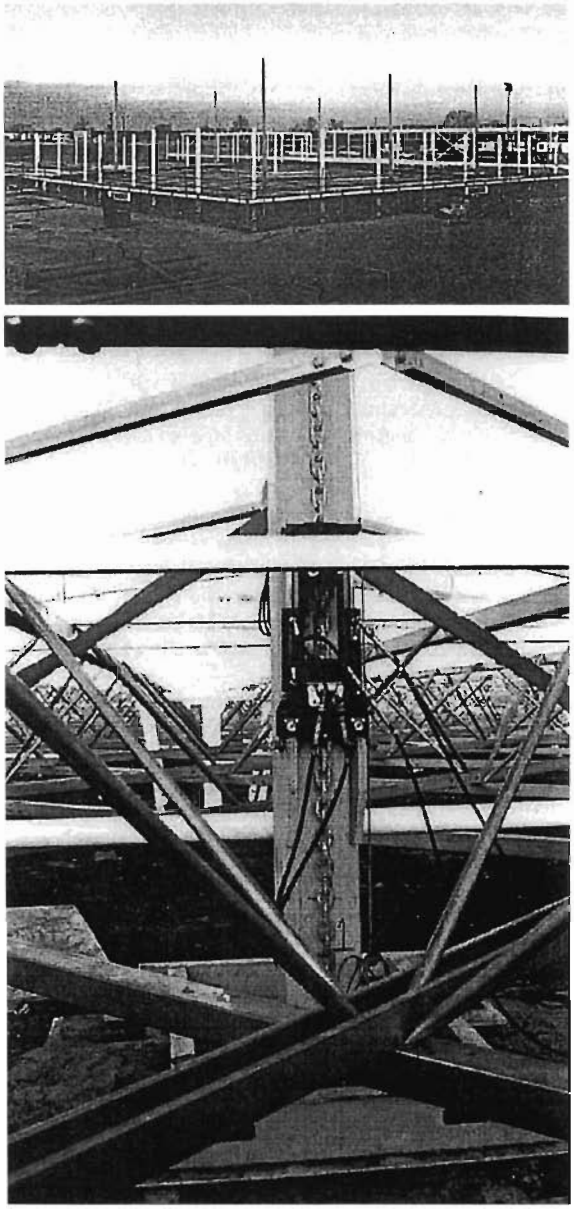


Fig 9. Chain lifting columns

ria which were considered; but there was apparently little thought given to the real behaviour of the lifting system, and no recognition of stress concentrations and their effect on fatigue. The hydraulic jacks were presumably purchased items, and assumed to be of the intended standard. According to the metallurgical investigation the necessary heat treatment of the rods had been omitted, so they were deficient in strength and toughness.

(1) A system must be considered in all its parts and understood in its totality.
(2) Where a system is not statically determinate, the consequences of small departures from nominal dimensions must be considered.
(3) Near misses should be reported and acted upon.
(4) Periodic inspection of fatigue cracks will not ensure safety where there are no alternative force paths.

Chain failure

A spaceframe roof structure was being raised by chains supported by six lifting columns. Centrally controlled, hydraulically actuated latches engaged in the chains and ensured that equal vertical displacements were applied at each lifting column. The force in each chain was known from the hydraulic pressure. When the roof was partly lifted, a chain link broke in two, and one piece travelled 50m; the structure was badly damaged. The chain of the adjacent column was then carrying 2.6 times the load carried by the failed chain, but was undamaged. When the roof was being lowered, a link in another chain failed whilst carrying a load smaller than that at which the first chain failed. The roof was then supported by four chains, none of which failed. The system had been successfully used on a previous occasion (Fig 9).

The chains passed over a pair of unfaceted, grooved pulley wheels, so the links were subjected to bending about an axis at 90° to the axis of bending caused by a straight pull. After the failure, a chain was tested when passing round one of the wheels. When the force in each leg of the chain was 3.8 times the force in the first failed chain, alternate links were bent to the radius of the wheel, but the chain was otherwise undamaged. No links had been visibly bent during the lifting operation, so most links were satisfactory, but some were not. Inspection of the chain revealed that a visibly different link occurred every 5m; the weld upset was less and the colour different.

A tensile test of a specimen from a sound link, across the weld, was satisfactory, and failure occurred away from the weld. Metallurgical investigation showed that the welded connections of the failed links were defective and there were signs that the copper grippers that applied force and fusing current to the connection had slipped. The broken links had non-ductile transverse fracture faces, and there was no evidence of out-of-plane bending. The fractures were not fatigue fractures, but indicated poor fusion. There was less upset in the failed links and in some other unfailed links, which also had evidence of gripper slip; lack of upset was found to be a good indicator of deficient welds. Magnetic particle inspection of a sound length of chain revealed no flaw before or after proof load testing; links were also bent over a 38mm radius former to a deflection of 7.5mm; no cracking could then be detected by magnetic particle inspection. Evidently, 5m lengths of well-formed and tested chains had been joined by deficient links.

(1) Chain safety depends critically on weld quality, which is sensitive to small maladjustments of the automatic welding equipment.
(2) It is important to know who is the actual manufacturer and to be assured that the prescribed high standards of manufacture and quality inspection are maintained.
(3) An inspection of the manufacturing process, quality assurance procedures, and testing facilities, is essential.
(4) For effective chain inspection, every link must be examined. Load testing does not assure quality unless accompanied or followed by inspection.
(5) A risk assessment should consider the safety and economic consequences of premature failure.

Fairlead failure

A fairlead is a pedestal attached to a ship's deck, around the head of which a mooring cable passes. When mooring a tanker, the welded connection of a fairlead to the deck failed suddenly; the fairlead became a projectile and caused the nylon mooring cable to impact a sharp edge, which cut the cable. The whiplash severed the lower legs of the two winchmen.

(1) The investigation led to the recommendation that the design rules should require that the connection to the deck should develop the strength of the fairlead and that the deck stiffening should be arranged to transmit the concomitant forces.
(2) A risk assessment should recognise that mooring forces can be exceptionally large and should consider the effect of possible failure of the rope or the attachments.

Bulkhead collapse

A tanker that had completed many voyages over 8 years without incident was preparing to leave the oil terminal. Having loaded oil, the forward tank, no. 1, was full, whilst the adjacent no. 2 tank, which was used for ballast, was empty. The engine had just been started when the crew noticed that the level in no. 1 tank was falling, whilst the level in no. 2 tank was rising. The reason can be seen in Fig 10. The departing bulkhead took with it a small portion of the ship's bottom, but the pollution was minimal, because the ship was grounded as a precaution.

Investigation showed that poor fit-up at the junction between the transverse bulkhead, the longitudinal bulkheads, and the bottom plating, had been remedied by the insertion of welding rods and other pieces of steel. Also, the penetration was generally poor: in many areas, the bulkhead, which was nominally 23mm thick, had pulled out, leaving the fillet welds on each side of the plate intact. This did not explain why failure occurred in calm water, having survived seagoing accelerations. There was no evidence that the tank had been over-pumped, and also the failure was said to have occurred 2h after completion of pumping. There was said to be little corrosion, although corrosion is a known problem in tankers[9].

After completion of pumping, the ventilator covers were closed, and would remain closed until the pilot had left the ship by helicopter, in accordance with normal safety procedures. Solar heating would have increased the vapour pressure, as it would have done on many previous voyages.

The piece of bottom plate, 28mm thick, which was found several metres away, was approximately semi-circular, the 690mm diameter coinciding with the bulkhead weld. The failure was initiated at the toe of the fillet weld, progressed by shearing around the circumference, and failed in tension at the crown. The piece had apparently been detached from the bulkhead when it struck a transverse frame. The bulkhead weld failure might have started in a region of deficient welding and progressed to the relatively well-welded region in the vicinity of the piece of bottom plate. The bulkhead weld might have suffered low-cycle fatigue cracking, caused by fore and aft flexing as the ballast and oil tanks were alternately filled, and perhaps high-cycle fatigue, caused by vertical and longitudinal accelerations. Having spread across the bottom of the tank, mostly at the butt weld between the bulkhead plating and the insert plates between the longitudinals, the tearing continued up the attachments to the longitudinal bulkheads. It seems unlikely that the transverse bulkhead would have pulled out the piece of bottom plate unless the bottom plate had suffered some damage. It is possible that fatigue cracking at the weld toe had penetrated into the bottom plate, but that was not revealed by the subsequent examination.

The welding was certainly deficient, and there were important welding deficiencies elsewhere in the structure. It seems unlikely that failure would have occurred if the welding had been satisfactory. Poor welding was the only clear reason that emerged to explain the failure.

The builders, the classification society, and the owner, all had inspectors on site during construction, but evidently the extent and quality of supervision did not match the magnitude of the task.

(1) Inspection reports should state areas inspected and results, during and after welding.

(2) Welders should be tested for the particular materials, configurations, and attitudes, that they will encounter.

(3) Fit-up limits should be specified and procedures for exceedances established.

Walkway collapse

The Ramsgate Walkway collapse was caused by design error, and the circumstances are fully described elsewhere[10]. A useful outcome of the tragedy is the recent CIRIA Report[3]. The lessons learnt from the collapse underlie the report, which was drafted by Posford Duvivier, with the involvement of the ports industry, Government, insurers, and Lloyds Register. The approach (and many of the recommendations) is relevant to other structures. An important recommendation is that the industry should set up a reporting system for structural or equipment failures and near misses. Also, Lloyds Register has published extensive new rules for linkspans and walkways[11].

Fig 10. Collapsed ship's bulkhead

Loss of the Derbyshire

The loss, with all hands, occurred in 1980, after 4 years' service, during Typhoon Orchid in the Sea of Japan, in a water depth of 4250m and without any distress signal being received. Bulk carrier losses are an international disgrace (108 in the last 8 years[12]) but, in general, receive little public attention, at least in the UK. Derbyshire however has been, and still is, a *cause célèbre*, partly because of the circumstances of the loss and partly because of the efforts of the British dependants of the crew, and of the seamen's union, to keep investigation of the tragedy alive.

There was circumstantial evidence that the ship might have broken in two at frame 65, just forward of the accommodation. That might have explained why no distress signal was received. Also it could suggest that the loss was caused by bad design or construction, which could affect compensation. A sister ship, Tyne Bridge, after nine years' service, had, in fact, suffered major brittle fractures emanating from structural discontinuities below deck at the frame 65 transverse bulkhead, but had survived. Repairs were made, using steel of grade D in place of the original grade A, and the ship served for a further 4 years before going to the breakers. Other sister ships had also experienced fatigue cracking below deck in the region of frame 65, and had been repaired, in some instances with modifications designed to reduce the discontinuity. It should be mentioned that local fatigue cracking is not in itself exceptional.

It transpired, however, that the fractures in Tyne Bridge had occurred at about 6°C when the ship was in ballast, which caused a tensile still-water bending stress in the deck at frame 65, whereas, when the loss occurred, Derbyshire was laden, for which condition the still-water stress at frame 65 was compressive. Also, the reported air and sea temperatures were 28°C and 27°C, and, according to Lloyds Register records of 40 brittle fractures, the highest temperature at which fracture had occurred was 24°C, the next highest was 19°C, and the average for the 40 ships was 3°C. In the writer's opinion, therefore, it seemed unlikely that catastrophic failure at frame 65 had caused the loss.

Since that initial opinion, underwater surveys have been undertaken, the most recent being extensive and detailed. The results, and associated analysis of 14 possible causes of failure, are described by Faulkner[12]. The paper, which considers hydrodynamic and structural effects, is authoritative and detailed, and should be read by anyone wishing to examine possible causes. Many recommendations for improving the safety of bulk carriers are given.

Faulkner concludes that, because implosion occurred on both sides of the bulkhead at frame 65 and because any compartment that imploded must have been intact at the time of sinking, deck fracture at frame 65 as the cause of the loss can be ruled out. It is contended that wave forces on hatch covers during the typhoon could have been much in excess of the strength of the covers, and that:

'Beyond any reasonable doubt, the direct cause of the loss of the m.v. Derbyshire was the quite inadequate strength of her cargo hatch covers to withstand the forces of Typhoon Orchid. This weakness to resist substantial water ingress is gross when compared with other major elements of the watertight boundaries of the ship's hull.'

'These hatch covers did meet the acceptable stress criterion of the 1966 International Convention on Load Lines. It then follows that the fundamental fault and cause of this tragic loss lies fairly and squarely in the altogether inadequate value and inappropriate nature of the loading and safety factor implicit in these Rules'.

Because of the fragmented nature of the wreckage, it seems unlikely that the cause or causes of the loss will ever be established with certainty. That does not diminish the importance of the investigations that have continued over 20 years. If causes were possible, they should be addressed in design.

The conclusion that deck failure at frame 65 did not cause the loss does not imply that fatigue cracking below deck, which occurred in all six ships of the class, is acceptable, nor does it imply that the use of grade A steel in primary structure is acceptable. Load specifications for hatch covers (which are primary structures inasmuch as watertightness depends on them) have been increased by some classification societies since 1980, but horizontal forces larger than are currently considered can be exerted on hatch coamings. Because of the wide variation of short-duration peak pressures[12], it is important that coamings should not be prone to brittle fracture under impact; they also are a primary structure.

The investigation by Skinner[13] on liquefaction of unpelletised iron ore, whether caused by progressive increase in pore pressure due to ship motion or by water ingress, has demonstrated the desirability of conveying iron ore in pelletised form. Four bulk carriers are known to have experienced major cargo shift; three were lost, one was towed to port. The phenomenon should not be dismissed because it caused only 1.1% of losses in the period 1960-94. In the period 1969-87, 128 bulk carriers were lost, i. e. seven p.a. In the period 1991-1999, 108 bulk carriers, of average age 19 years, were lost, i. e.13 p.a. However it appears that about 35% were caused by navigational errors[12]. Fire and/or explosion was another important cause. Structural failure is only one of several causes that require action to improve safety (there is no suggestion that crew performance contributed to the loss of Derbyshire). The age of ships lost suggests that corrosion could be an important factor. The increase in annual casualty rates since 1991 suggests that, if lessons have been learnt, they have not been applied.

Faulkner, in particular, and the many other authors listed in ref. 12 are to be congratulated for the sustained effort over 20 years to improve understanding and knowledge. At the time of writing (December 1999), the parties to the formal investigation have been asked by Mr Justice Colman to provide provisional answers to a list of questions[14].

Whilst research is an ongoing requirement, it seems to the writer that the most urgent problem is not lack of knowledge, but lack of implementation.

(1) Marine losses should be more widely publicised.
(2) Discontinuities should be minimised and their effect taken into account.
(3) Grade A steel in primary structure should not be permitted.
(4) Shipping is international and competitive, so stringent international regulations, accompanied by enforcement, are essential for safety.
(5) Condition surveys should be regular, competent, and acted upon.
(6) Where relevant, the effects of possible liquefaction should be considered.

Early warnings

The effects of contaminated aggregates on concrete durability are now well known, but the rapid deterioration of some structures in the Middle East in the 1970s can be used to emphasise that the effects of exceeding specified limits of chlorides and sulphates are real and can have major economic consequences.

A straight starter bar broke when a small deviation was being rectified, casting doubt on the ductility of all similar bars on the site. Was this a unique occurrence? Are site bend tests advisable?

The driving record for a precast concrete pile indicated abnormality, and this was confirmed ultrasonically. Excavation showed that shear failure had caused the reinforcement to develop a S-bend. A central hole provides a simple means of checking integrity.

None of the above events created a safety risk: the first had major cost implications for clients and contractors; the second caused disruption to programme, and possibly was a unique event; the third emphasised the need for careful driving records and detailed inspection, assisted perhaps by automatic plotting (a central hole facilitates quick and convincing checking).

Lessons and actions

(1) With diligence and vigilance, safety and quality may be maintained without regulations; regulations can be helpful, but without diligence and vigilance they will not be effective.
(2) The essence of risk assessment is that the designer considers the effects of all possible eventualities, as distinct from checking that specified loads can be supported assuming that materials perform as expected. Risk assessment can be assisted by a checklist compiled with the help of experience. However, it should be made clear that the list is intended to stimulate and not to inhibit the imagination.
(3) Specialisation can lead to partition of responsibility. An overall view of parts and effects is required: e. g. the safe and reliable operation of linkspans and walkways in ports depends on structural, mechanical and electrical components, as well as on aspects of ship operation. The CIRIA guide[2] on procurement, operation, and maintenance of these structures therefore recommends the designation of a system engineer who will appraise the design, operation and maintenance of the whole system.
(4) Experience should be fed back promptly to design practice, to Codes, and to engineering education.
(5) Engineering courses should include an obligatory module devoted specifically to safety and performance. The module should include an introduction to an engineer's moral and legal responsibilities in design, construction, and operation, and to risk assessment and analysis.
(6) Courses should at least make students aware of the questions that need to be asked regarding the properties and performance of construction materials.
(7) Engineering courses should ensure that computer aided analysis, and design Codes, are not seen as a substitute for physical grasp.

(8) Students should experience the art of identifying the various actions, responses, and other phenomena that could occur in service.
(9) Provision for inspection, maintenance, and safe operation, should be included in design, and clear instructions should be issued. The effects of deficient maintenance or operation should be considered in the risk assessment.
(10) In the case of movable structures, operator training and qualification is essential.
(11) In many circumstances, it is necessary to ensure that connections should be able to develop the strength of the parts joined; where this is considered to be unnecessary, the justification should be recorded.
(12) The circumstances under which a structure could become a mechanism should be considered.
(13) The designer should have evidence that material properties are as specified. The identity of the manufacturer (as distinct from the vendor) should be known.
(14) Lifting structures and moving structures demand an especially high standard of design, procurement, operation, and maintenance.
(15) For multidiscipline systems, responsibility for interaction between components, and for coordination of disciplines, should be clearly allocated.
(16) Regulations are now so numerous that consultants are being employed solely to advise on regulations: e. g. ship-to-shore structures are subject to nine sets of regulations. Each has its virtues, but digesting and fulfilling the formal requirements of the totality might demand disproportionate effort, to the detriment of design, analysis, checking, and supervision. Guidance that is specific to particular types of structure, including a distillation of relevant regulatory requirements, can help to realise the intention, whilst redressing the disproportion.
(17) Engineers should be aware of the danger of their imaginations being inhibited by regulations and design Codes, which should make clear that they do not cover every possible eventuality. The designer, constructor and operator should see their prime objectives as being to ensure safe and efficient performance of the structure or machine. They should then check that the regulations have been satisfied and that any relaxation of Code requirements can be justified.
(18) Accidents have been caused by an incorrect visualisation of the action of a component or system, by omitting consideration of a certain phenomenon, or by not taking account of some operational circumstance. Before embarking on calculations, it is important to write down the loadings and phenomena to be considered and the idealisations to be made in the analytical model. Reference would be made to the risk assessment.
(19) Connections are of special importance: they usually determine fatigue life and the mode of fatigue failure. If they are at least as strong as the adjoining parts, they will greatly enhance the robustness of the structure in the event of extreme or unforeseen loading. If the integrity of the components is maintained, the consequences of collapse will be less severe. Connections also have a major impact on cost.
(20) When designing against fatigue, the redundancy of the structure should be considered. If alternative force-paths exist, crack monitoring might be an acceptable means of delaying repair or strengthening. If there is no alternative force-path, failure follows quickly after crack detection, and immediate action is required. Therefore, it is logical in design or assessment to allow a greater margin against calculated fatigue life when there is no alternative force-path.
(21) The reporting of minor incidents and near misses is very important. If a major disaster occurs, action to prevent a recurrence will probably be taken. If the minor incidents and near misses are reported and disseminated, major disasters could be prevented.
(22) Notwithstanding the proper emphasis on safety, it should be remembered that even failures that are not life threatening can have major economic consequences. Safety and economy are compatible.
(23) A system is required for collecting, collating, and disseminating information on failures and near misses. The scope would need careful consideration.

Acknowledgement

Some of the incidents described were investigated by Chapman & Dowling Associates and came our way through the reputation of my colleague, friend, and erstwhile partner, Professor Patrick Dowling, FREng FRS.

Appendix A

The following extract from ref. 3 lists operational eventualities which it is considered should be included in a risk assessment for linkspans:
'The contingencies to be considered will depend on the type of facility, its surroundings, and the location of emergency services. For linkspans they will probably include:

- ship collision
- failure of sensors on shore or on board ship
- fire on shore or on board ship
- structural failure of linkspan lifting equipment
- failure of linkspan bridge components, including bearings
- vehicle failure or collision with linkspan
- extreme weather conditions (waves, wind, snow, ice)
- sabotage, especially of vulnerable components
- operational error
- strike action
- failure of ship's equipment required for linkspan operation

A similar assessment is required for walkways.
It will then be possible to write the operating instructions and design the training schemes for the operators'.

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