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The design of ship-to-shore linkspans for ro-ro terminals

This paper is a broad introduction to the issues facing designers of ship-to-shore linkspans for roll-on-roll-off ferry terminals, including mechanically lifted, pontoon, semi-submersible and integral tank types, outlining some key problems associated with each type. It discusses the development of design guidance since the 1994 Ramsgate walkway collapse, leading to the publication of BS 6349-8 in the UK in 2007 with guidance on lifting equipment, transition geometry and loadings. Ship damage and wave action on linkspans are also discussed.

The design of linkspans for roll-on-roll-off (ro-ro) terminals involves an exceptionally wide range of issues and requires a large number of engineering competencies to ensure a successful outcome. It is not a subject that is familiar to many civil or structural engineers or indeed many port operators outside the ro-ro industry. This paper covers the following

- the definition of 'linkspan' and a general description of the four main types
- the changes in design approach that have resulted from the publication of BS 6349-8 (BSI, 2007)
- ship damage and wave action.

The ro-ro mode of sea transport is increasingly important, particularly in the UK where it represents a 30% greater volume of trade than that carried in container-only mode (DfT, 2008) (Figure 1). These trades rely on the existence and reliability of linkspans to transfer cargoes from ship to shore.

What is a linkspan?

The term 'linkspan' is now internationally used to describe the means by which vehicles drive from shore directly onto a ship deck, no matter what the level of tide or attitude of the ship. It appears to have started out as a trade

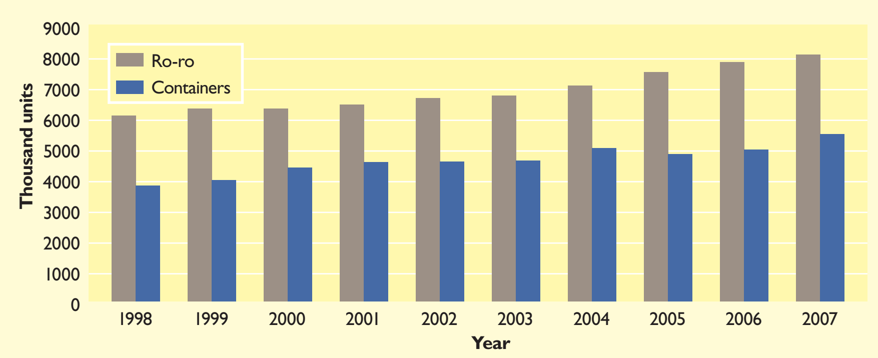

Figure 1. Ro-ro and container trade to and from the UK – ro-ro traffic exceeds container-only traffic by around 30%

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name for a particular type of semi-submersible facility but in time its scope has expanded to refer to a whole range of facilities of at least four totally different types (see Figure 2)

- mechanically lifted – these are raised and lowered using lifting equipment such as hydraulic cylinders, rope winches or rack and pinion
- pontoon and link bridge – the interface with the ship is a restrained pontoon that floats up and down with the tide and is accessed by a link bridge
- semi-submersible – its self weight is supported by a submerged float but the traffic is supported by a connection to the ship (rope or shelf)
- integral tank – this is similar to pontoon but the pontoon is rigidly connected to the bridge.

As a general rule, the relative costs of the different types relate to the activation method. Hence mechanically lifted linkspans include the cost of the lifting machinery, but the floating types include the costs of the floating body. The size and weight of material making up the floating body will determine the relative economics of the different types. For instance, the semi-submersible system uses the least steel of the three floating types and, as a consequence, tends to be the cheapest. Conversely, the pontoon and link bridge type uses the most material and as a result has tended to be the most expensive.

However, other factors have governed the choice of linkspan. For example, there is a considerable economy of scale when more than one berth can be served from the same pontoon. Also, semi-submersible facilities suffer the operational disadvantage that they must be physically supported by the ship and the operation of connecting the pendant ropes to the vessels can be a considerable inconvenience. While these types are cheap, none have been constructed over the last 10 years to the author's knowledge.

Integral tank and mechanically lifted linkspans have been the most frequently constructed facilities in recent years, though several pontoon and link bridge systems have also been constructed in the UK notably at 12 Quays terminal in Birkenhead, the Humber Sea terminal berths 4, 5 and 6 at North Killingholme (two pontoons) and the nearby Tor Line terminal at Immingham.

Ciria report C518 *Safety in ports – ship-to-shore link-spans and walkways* was published in 1999 (Ciria, 1999) and included a survey of linkspans in the UK and north-west Europe, from which the numbers of each different type were counted. This was not an exhaustive survey and was limited to the responses received. The results are shown in Figure 3, along with

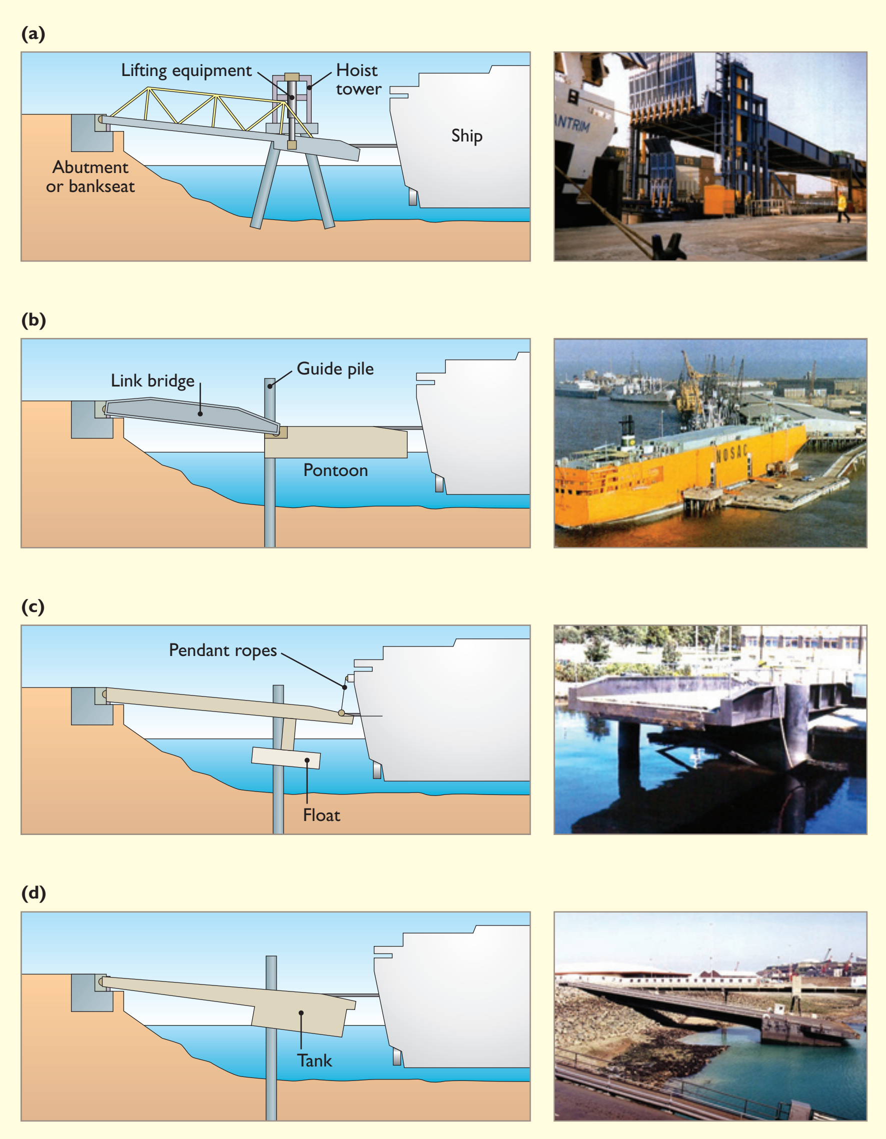

Figure 2. General arrangement and example of each the four main types of linkspan: (a) mechanically lifted, (b) pontoon and link bridge, (c) semi-submersible and (d) integral tank

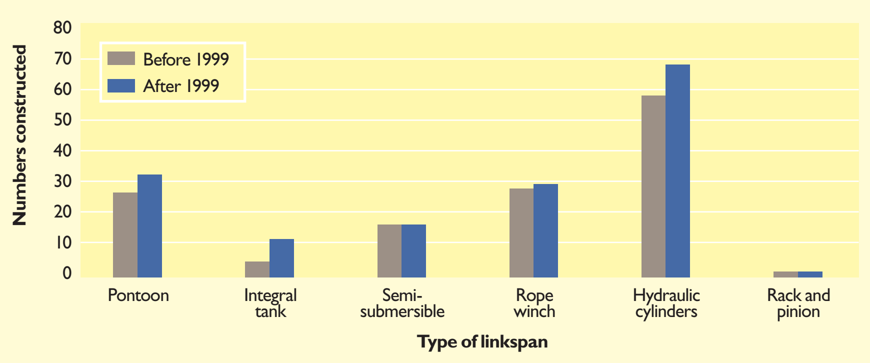

Figure 3. Numbers of different linkspan types in the UK in 1999 and 2009 – integral tank and hydraulically lifted have been the most frequently constructed types in recent years

updated figures based on the author's information. From this it is apparent that no new semi-submersible facilities have been constructed since 1999 and that the greatest percentage increase has been in integral tank linkspans.

Development of design standards

Linkspans became firmly fixed in the public mind after the Ramsgate disaster in 1994, in which six people died when a passenger walkway collapsed and fell some 6 m. The linkspan at Ramsgate was of the pontoon and link bridge type, with a pontoon of relatively compact area. However, the facility also included a high-level passenger walkway that was supported on towers on the pontoon (see Figure 4).

Chapman (1998) clearly explains the major cause of the accident, which was a design error in the bearing system for the high-level walkway. The implications of having a torsionally stiff passenger walkway spanning onto a floating (and therefore mobile) body were not taken into account and the stresses in the bearings exceeded their design values by a very large factor. It is typical that many problems associated with linkspans relate to their articulation and bearings rather than the design of their main structural members.

Following the Ramsgate incident and the subsequent court cases, in which the designer, the classification society carrying out the design assessment and the port authority were all found guilty and fined, the port and construction industry undertook several tasks to provide guidance to the industry. The most relevant action in the current context was the commissioning and drafting of a new part 8 of the UK maritime structures code BS 6349, dealing specifically with the design of ro-ro ramps, linkspans and walkways (BSI, 2007). The contents of part 8 are summarised in Table 1.

Historically, linkspans have been designed by organisations that have extended their experience from a track record of designing highway bridges and organisations that have extended their experience from a track record of designing ship equipment. The two industries have developed different design methods.

The bridge industry has developed design methods based on ultimate-limit-state techniques using codes such as the various parts of BS 5400 on steel, concrete and composite bridges (BSI, 2005) and, more recently, the Eurocodes. The shipping industry has devel-

Table 1. Outline contents of BS 6349-8:2007 (BSI, 2007)

Section	Key contents
0 Introduction	• Defining that structural design calculations can be carried out using shipbuilding-type design codes (Lloyd's rules) (Lloyd's Register, 2008) as well as bridge design codes (BS5400) (BSI, 2005). • Defining ultimate and serviceability limit states with respect to linkspans. • Defining the operating and extreme tidal conditions. • Highlighting methods of adjustment, requirements for prevention of collapse and maintenance conditions.
1 Scope 2 Normative references 3 Terms definitions and symbols	No special content.
4 General recommendations	Dealing with a series of practical issues including • highlighting the need for planning to decide on the appropriate type • requiring the design is based on a fundamental risk assessment • highlighting the need and requirements for an operation and maintenance manual • highlighting factors affecting the design parameters such as layout, ship type, ship control methods, the required degree of automation in any machinery, adjustment methods, types of vehicles, wave conditions and water levels • highlighting key environmental conditions affecting design including environmental impact, meteorological situation, bathymetry, geotechnical considerations and water quality (including propensity to microbiologically induced corrosion) • requiring load testing similar to that required by the Supply of Machinery (Safety) Regulations 1992 (HMG, 1992).
5 Types of structure	Highlighting the types listed in section 0 above and doing the same for passenger walkways.
6 Geometry	Dealing with • horizontal geometry including roadway width, geometry of ship interfaces (including the different types of ship ramp and also fingers from linkspan to ship) and ship movements while alongside a berth • vertical geometry including maximum gradients, transition geometry and vertical headroom clearances for double-deck linkspans.
7 Loads, movements and factors	A listing of the loadings including • dead loads including loads from ship ramps and finger flaps • wind loadings • temperature • hydrostatic loads • current forces • wave loadings • berthing loads (from fenders and so on) • mooring loads • other ship induced loads such as propeller wash • highway loadings, which is varied compared to BS 5400 (BSI, 2005) to allow for the special characteristics of ro-ro operation (e.g. segregated loading, controlled lane loadings) • port vehicle loadings, including the very heavy loads exerted by fork lift trucks and cargo roll-trailers with double-stacked containers • walkway loads • vehicle collision loads • fatigue loading • loads from operational equipment • loads on vehicle and pedestrian restraint systems (crash and safety parapets).
8 Structural analysis and design	This section highlights, among other issues • highlighting the design codes available including BS 5400 (BSI, 2005) and Lloyd's rules for the classification of linkspans • defining how to interface with BS 8004 (BSI, 1986) for foundation design • highlighting the key issues to consider in articulating the facility • highlighting stability issues, in particular the need to ensure hydrostatic stability for buoyant linkspans • discussing the design the bearings with particular recommendations that robustness is a particularly important quality for linkspans • discussing guides to maintain the position of linkspans throughout the tidal movements • the key issue of redundancy of lifting systems • the means to integrate the design with that of any operating machinery • arrangements to park the linkspan safely while idle or being maintained • the use of proprietary items in the design.
9 Furniture, finishes and corrosion protection	Dealing with issues such as • road and footway surface treatment • vehicle and pedestrian parapets and barriers.

Figure 4. The double-deck pontoon and link bridge linkspan at Ramsgate, UK – the original high-level walkway collapsed in 1994 killing six people, triggering a major revision of British linkspan design codes

oped design methods based on working-stress approaches and use classification rules which are, in effect, codes of practice developed by the classification societies. Indeed, Lloyd's Register of Shipping, one of the premier international classification societies, has gone further and developed a set of rules that apply specifically to linkspans (Lloyd's Register, 2008). The committee developing BS 6349-8 (BSI, 2007) decided it was important to permit the use of both approaches so that the procurement of linkspans could be governed by the standard no matter what type of design organisation was responsible for it.

The following sections highlight some practical aspects of using the new code.

Risk assessments

BS 6349-8 (BSI, 2007) requires that, prior to attempting any design work on a linkspan, a fundamental risk assessment should be carried out. It is most helpful to carry out the identification of hazards by including in the register a series of different scenarios

- facility standing idle
- vessel approaching the facility to berth
- ship ramp is on the facility and traffic is being transferred from ship to shore or vice versa
- vessel departing
- facility being maintained.

Since the range of hazards present in each type of linkspan and location is very different, it is important to avoid simply copying a previous hazard register.

Safety of lifting equipment

The safety of lifting equipment is one of the most controversial issues to be resolved in BS 6349-8 (BSI, 2007). Clause 0.3.3 makes a distinction between two types of lifting system

- method I – in which the linkspan is adjusted by lifting machinery that only supports the self-weight of the linkspan followed by pegging the linkspan into the adjusted position using a shear pin or similar
- method II – in which the linkspan can be adjusted by lifting machinery when loaded with vehicles or passengers.

Method II is the most common type of system.

Linkspans are one of only very few types of facility in which persons are on board an adjustable structure that is supported by its lifting machinery. Although there are many moveable bridges throughout the world, nearly all of them are in a secure position on fixed bearings at the time the general public crosses them. In that respect, linkspans present significantly greater risks to the public than normal moveable bridges. Therefore, clause 8.8 makes the following statement

> 'Where the linkspan is to be supported by a mechanically lifted suspension system using method II (see 0.3.3) from a support structure, an alternative load path should be provided in the event of a failure in any element of the primary load path of that system, inclusive of the connections to the support structure.' (BSI, 2007)

There are also other rules for enhanced partial factors at the connection points and another general rule to promote ductile rather than brittle failure in support structures. There is now general acceptance of this rule and all recent mechanically lifted linkspans include redundant load paths. The most common way of providing this is by the introduction of a second hydraulic cylinder either as a simple back-up facility to be activated in emergency or with shared loads. Both types require suitable control equipment. Figure 5 shows an example with duplicate cylinders.

Figure 5. Berth 51, ro-ro ramp 1 in Dublin, Ireland showing duplicate cylinder supports as required in BS 6349-8 (BSI, 2007)

Geometry

For a many years, the designs of ro-ro ramps in the British sector has been influenced by ISO 6812 (BSI, 1984), which was based on research carried out in the late 1970s. It needed to be superseded because

- ship threshold heights have increased significantly, partly as a result of enhanced ship stability rules
- safety requirements on heavy goods vehicles require comparatively low tailgates and mid-wheel protection barriers leading to lower effective ground clearances
- there are new vehicle designs, such as certain new classes of highway trailers.

The substantial change in the recommended shape for end profile is shown in Figure 6. This was necessary to improve the transition

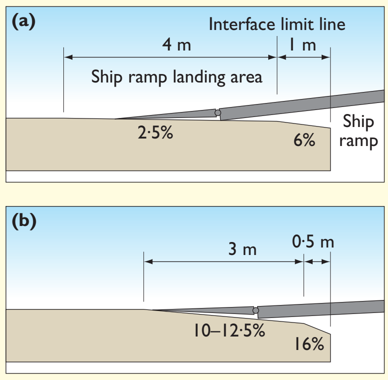

Figure 6. Comparison between the end profiles of linkspans in (a) ISO 6812 (BSI, 1994) and (b) BS 6349-8 (BSI, 2007) – the change was needed due to higher ship threshold heights and lower trailer designs

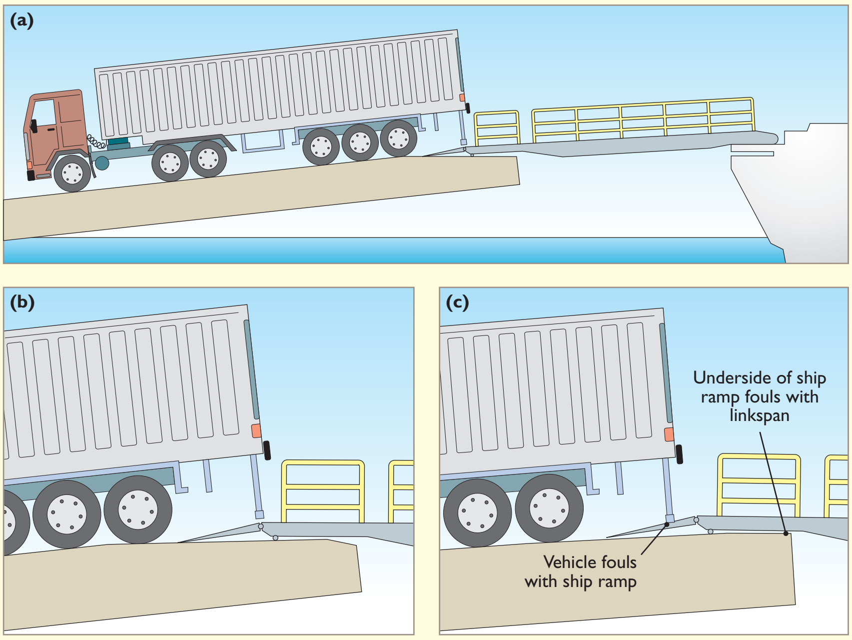

Figure 7. Typical ship ramp/linkspan relationship at high tide (a), with (b) detail of BS 6349-8 profile (BSI, 2007) and (c) problems caused with old ISO 6812 profile (BSI, 1984)

Figure 8. Segregated traffic at Dover ro-ro terminal – such segregation requires a different approach to traffic loadings compared with those used for standard road bridges

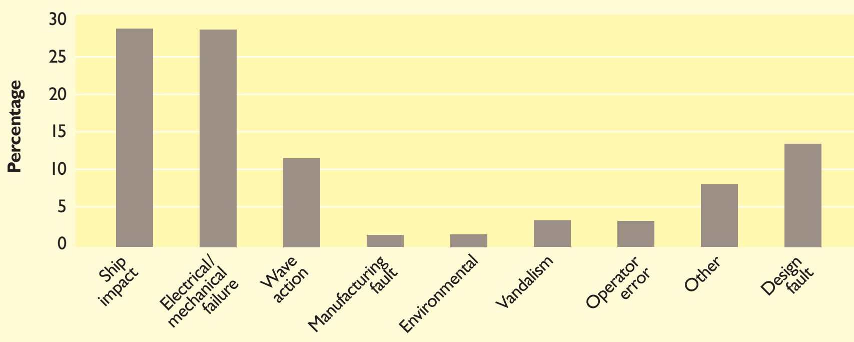

Figure 9. Frequency of causes of significant incidents at UK linkspans – ship impact is the highest risk

profile particularly for the high-tide situation where there is often a substantial upward slope from shore. Figure 7 indicates the benefits of the new recommendations. BS 6349-8 (BSI, 2007) also recommends that the profile shown in Figure 6 should be regarded as indicative only, because there are sometimes significant variations of ship ramp design.

Loadings

BS 6349-8 (BSI, 2007) gives guidance on the loading of linkspans that takes into account the following factors.

- Traffic on linkspans is supervised. The numbers of lanes of traffic are governed by operational procedures as much as by linkspan carriageway width.
- For cargo modes where unaccompanied trailers are handled without their highway tractors, they are loaded using port tractor vehicles. The traffic loading in this case can be heavy but sparse.
- When loading queues of driver-accompanied ro-ro trades, heavy goods vehicles are usually fully segregated from cars (see Figure 8), meaning that the lane loads on longer spans can be expected to be higher than those experienced with normal highway loads. Hence the loading in BS 6349-8 (BSI, 2007) has several important differences compared to the highway loadings defined in BS 5400 (BSI, 2005).
- Traffic transit is at slow speeds and therefore there will be lower impact factors except at changes in geometric transition.

Particular design problems

The following is a sample of some issues that linkspan designers need to consider.

Frequency of accidents

Ciria report C518 (Ciria, 1999) included information on accidents and incidents that had occurred to linkspans that had caused significant problems. Of a sample of 177 surveyed in 1999, 34% had experienced significant incidents of one type or another. It will therefore be apparent that linkspans do not have a good reliability record compared to static structures.

Figure 9 was also included in the Ciria report and gives the percentage of each type of major incident as a proportion of the total incidents for which data was given. It is apparent that ship damage, electrical/mechanical failure and wave damage are very important factors. The author is aware of two further failures of rope-lifted equipment (at Calais, France and Turkmanbashi, Turkmenistan) and one of hydraulic lifting systems (Kuantan, Malaysia).

Ship damage

BS 6349-4 (BSI, 1994), which is presently under revision, gives guidance on the design of fendering systems for ships but, for ro-ro linkspans, it needs interpretation. Figure 10 indicates the two berthing modes relating to ro-ro berths and Table 2 indicates what this means in terms of resisting force. Note that the approach velocities listed are those for an approach against the linkspan and not those against the fenders of the berth or quay. That for berthing mode b) comes from note 1 of clause 4.7.6.3.2 of BS 6349-4 (BSI, 1994).

- Berthing mode b) assumes the ship is normally brought to rest alongside the side fenders and the berthing velocity at the linkspan is intended to deal with minor accidents only.
- Berthing mode c) deals with the situation where the linkspan, or nesting fenders on either side, is used as the main berthing impact point during an approach manoeuvre. The forces generated when accommodating the higher approach velocity for berthing mode c) are up to 14 times higher than those generated in berthing mode b).
- The very high forces involved in berthing mode c) with moderate-sized ships can lead to situations where a viable design is not even feasible.

By careful location of the berthing facilities around the linkspan, it is usually possible to avoid having to design for berthing mode c). For instance, simply lengthening the berthing

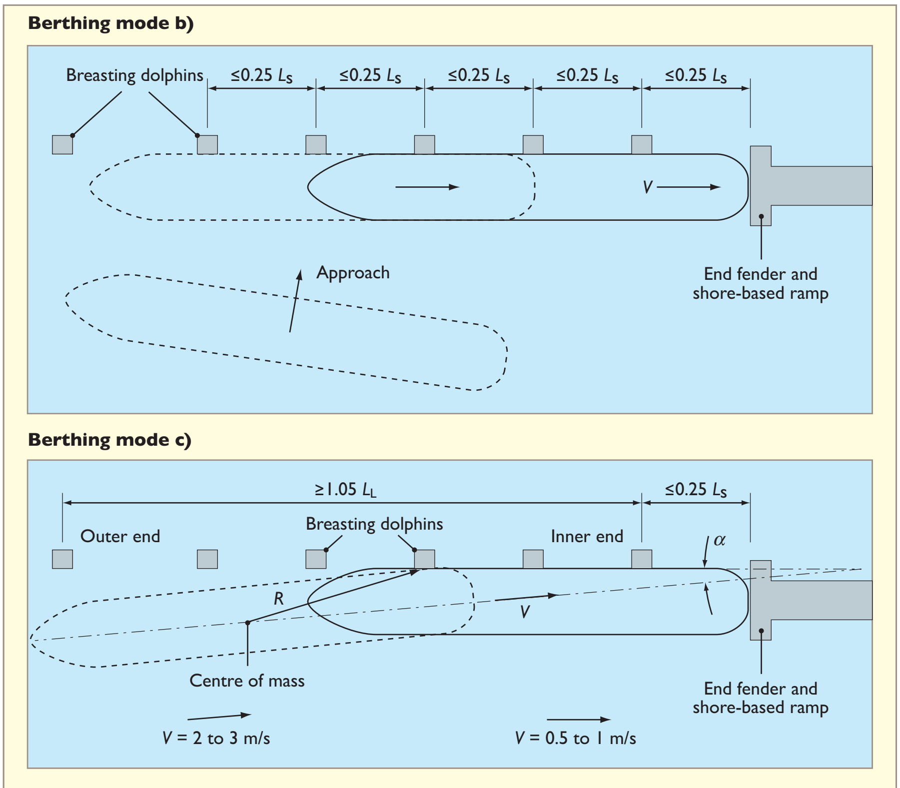

Figure 10. The two berthing modes applicable to ro-ro linkspans given in BS 6349-4 (BSI, 1994) – the forces involved in mode c) can be unfeasibly large

Figure 11. Nesting fenders at Dover, UK for berthing mode c) protection of linkspan

Table 2. Example comparison of end fender berthing energies and typical forces

Berthing mode	Ship displacement: t*	Approach velocity: m/s	Berthing energy ($0{\cdot}5Mv^2$): kN m	Possible fender products†	Typical force generated by fenders: kN
b)	12 000	0·15	270	2 no. UE 900 × 1000 Unit Element fenders rubber grade E2·0, total energy 306 kN m	740
c) (lower limit)	12 000	0·5	3 000	5 no. UE 1600 × 1000 Unit Element fender rubber grade E2·8, total energy 3005 kN m	4 075
c) (upper limit)‡	12 000	1·0	12 000	2 no. SCK 3000H Cell fenders rubber grade E1·8, total energy 12 200 kN m	10 572

Notes
* The ship size does not represent the largest vessels that might use such a facility
† Products selected take no account detailing requirements and are for example only to demonstrate the force differences that arise.
‡ Different products are required with longer travel in order to keep forces a little lower. The forces are nevertheless exceptionally high.

Figure 12. Vlaardingen terminal in the Netherlands, showing BS 6394-4 (BSI, 1994) berthing mode b) protection to outer edge of linkspan (adjacent protecting dolphins not shown) (courtesy MacGregor RoRo, Gothenburg)

face for the ships can be enough. Figures 11 and 12 show two different fendering systems. Most modern linkspans are based on having fenders between the linkspan and the abutment rather than at the fender face. As a protection against berthing mode b) accidents, this is the most efficient way to provide protection. In general, the author strongly recommends against using the linkspan itself to support the fenders for berthing mode c) since it greatly increases the probability of significant damage to the linkspan, which could put the berth out of action for long periods of time.

Wave actions

Waves are one of the most important environmental actions affecting the design of linkspans. There is sometimes an assumption that linkspans are constructed in sheltered locations. However, this is far from the case and there has been a significant trend towards constructing more linkspans in locations where wave actions can be large.

It is not always obvious where a location is exposed or protected. The 12 Quays terminal and pier head at Liverpool are some 6 km from the mouth of the river but, because of successive reflections between vertical Victorian river walls, significant wave heights of 1·5–2·0 m have been experienced. In these circumstances it is very important to assess carefully the wave actions on a floating pontoon and, in the case of 12 Quays, a programme of physical model tests was carried out by ABP Mer in 1999.

Figure 13 shows the dramatic results of a restraint pile failure, which highlights that the issue of wave forces is more than a theoretical consideration. This incident took place in a location that also appears, at first sight, to be in a sheltered part of a harbour. In many ways, a proper assessment of wave actions and effects is one of the most important activities in selecting a suitable linkspan type. Waves can even have important effects on lifted linkspans, as is indicated in Figure 14. This illustrates a situation where a designer might normally not expect to have to worry about waves, but which exists in a large number of facilities in use at the present time.

Conclusion

In this short space it has only been possible to touch on a few of the many issues that linkspan designers have to deal with. For instance, the paper has not covered the myriad problems associated with the design of upper decks and the additional geometric, functional and safety issues that result. Neither has the paper covered the articulation and bearings for linkspans, which require a rather more robust approach compared to those on land-based bridges. The complicated issue of finger flaps for upper deck bridges (as in Figure 5) has also not been discussed.

However, it is hoped that this paper gives a sufficient overview to highlight some of the key issues for which linkspan design engineers must find solutions. It is also hoped that it will give an insight into the range of skills that an organisation procuring a linkspan must bring to the project.

The main issues in BS 6349-8 (BSI, 2007), the UK code of practice for the design of ro-ro ramps, linkspans and walkways, have been discussed. This standard is now well established in the industry and is routinely referenced by specifiers and designers of linkspans.

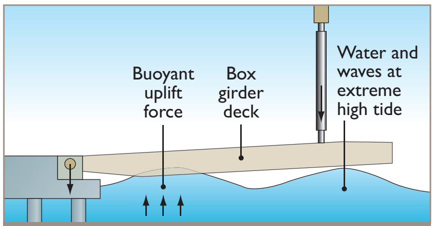

Figure 14. Wave action on a mechanically lifted box girder linkspan – such actions are often unforeseen

Figure 13. Restraint pile failure due to wave action at east berth linkspan in Elizabeth harbour, Jersey

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