DISCUSSION

HULLFORM & HYDRODYNAMIC CONSIDERATIONS IN THE DESIGN OF THE UK FUTURE AIRCRAFT CARRIER (CVF)

M E Campbell-Roddis, British Aerospace & BAE Systems, Glasgow & Filton (Bristol), UK
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COMMENT

Prof D Andrews, **FREng**, **PhD**, **FRINA**, **RCNC**, Vice President

The author is to be congratulated in producing a paper for the journal on an important aspect (hydrodynamics) of a design, which was taken to a considerable level of definition before not being proceeded with. The fact that we so rarely get visibility of the thinking and effort behind "abortive" designs – so very little was allowed to be preserved of the cancelled CVA01 of the 1960s – and that this can be compared to the separately evolved, subsequently fully design and, now in 2017, about to go into service QUEEN ELIZABETH (QEC) carrier, makes this a very worthwhile document for the Transactions.

Not only can the various detailed conclusions on the hydrodynamically related design choices be read for their input to the BAE Systems alternative to the Thales design, that was finally developed into the QEC (see S Knight's 2009 RINA Conference paper), the paper also provides general insights into the interaction of one specific topic (hydrodynamics) with wider design developments. This can be instructive to future designers of complex ships – not just aircraft carriers. It could be argued that despite the growing capabilities of CFD tools, that there still appears to be a need for substantial model testing of discrete elements of the hydrodynamic design, as described. Would the author like to comment as to whether he sees this dual need for CFD and physical model testing likely to continue whenever new designs "are just that little bit too different" and how one might judge the latter?

Given this discusser set up the procedure for the extensive UK Ministry of Defence (MoD) concept work on the Future Carrier, when Head of Concept Design in DFP(N) in the early 1990s (Andrews, 1994), it is surprising that the author does not refer to the paper that reported that extensive in-house design exploration work undertaken before the "competitive MoD funded feasibility level work that this paper covers. Eddison and Groom's (1997) paper lists the five ship option types (notably the four STOVL options with 15 to 40 aircraft and two CTOL options with 26 and 40 aircraft). These authors also list some 16 design investigations, ranging from side lifts and flight deck arrangements to shock and vulnerability measures as well as hull form and propulsion fits, directly relevant to the current paper. It is presumed all this work informed not just the Staff Target in 1998 but was also provided to the two industry design teams? What is of interest is not just that these discrete topics go well beyond the hydrodynamic but how much they all have a bearing on the seemingly hydrodynamic specific issues, showing so much of the design process is so clearly interrelated.

It would also be insightful if the author could add a further comment addressing, beyond the timescale of the paper as it stands with the 2003 decision to proceed with the Thales design, how the hydrodynamic conclusions of this work matched the subsequent design development. It is noted that there has been a subsequent paper on the QEC's hydrodynamics (Harris *et al* of BMT DSL, Thales Naval Ltd. & QinetiQ (2009)), which can be seen to have taken up many of the choices made by the author's early team's efforts. Could the author comment as to both the commonality and difference between these two sequential hydrodynamic efforts?

On the hydrodynamic aspects of the carrier design, it is interesting to observe that in our earlier paper on the very novel INVINCIBLE design (Honnor & Andrews, 1982) the only aspect of hydrodynamics that we thought necessary to flag up was that of the seakeeping analysis undertaken to assess the wetness implications regarding the location of the foremost ship side openings outboard of the hangar. This was probably not seen as a concern for the much larger and, specifically, considerably longer, QEC but I would like to ask if this one (significant) hydrodynamic issue in the INVINCIBLE design was also investigated in the BAE Systems CVF design? When design comparisons are drawn, too many just compare design displacements – however a much better comparison of size, for these essentially space driven vessels, is that of gross enclosed volume. Thus that for INVINCIBLE is 80,000m^3 which is directly comparable with HERMES, its companion carrier in the Falklands' campaign although the latter was some 50% heavier.

In Section 7.2 in the first of the set of five bullet points on "key discriminators" the author invokes a structural issue when adopting the "highly flared midsection" (Figure. 4) in preference to the traditional "sponson" style (Figure. 3). This non-hydrodynamic issue is said to simplify the structural arrangement ("by eliminating the need for continuous longitudinal bulkheads"). Could the author say how this "elimination" was confirmed? Thus without continuous longitudinal bulkheads, was there sufficient stiffness in the hull girder? This aspect of strength was a concern in the INVINCIBLE design (see Honnor & Andrews, 1982), which had two sets of longitudinal bulkheads port and also starboard to ensure the longitudinal stiffness of the tall (three decks) and (amidships) narrow hangar was transmitted efficiently into the hull girder. It was only when the SESAM FEM analysis finally delivered (after the structure was built due to the novelty of the modelling of a whole ship's structure in the 1970s) its results that the assurance of the maintenance of the hull girder's structural stiffness was shown to be sufficient. In fact, despite the current author's comment in Section 2 of the "relatively light structural scantlings" of INVINCIBLE, the high D/L hull ratio meant that the midships longitudinal strength was actually massively adequate. This was due to the scantlings of the flight deck and hanger deck being (like the aircraft lifts) primarily designed for future aircraft loadings.

In repeating my thanks for this paper on an unfulfilled design, I would like to re-iterate its value in showing how just one element of the naval architect's concern in working up anew ship design (that of hydrodynamics) is both sophisticated and largely interactive with the other elements of the design (e.g. strength, stability, configuration and fighting (aircraft) effectiveness). It would be good to have the aspects of producibility and, eventually, aircraft operability presented alongside this presentation and its companion paper (Harris et al, 2009) and indeed the 2005 general aircraft carrier configurational paper by this discusser (Andrews, 2005).

AUTHOR'S RESPONSE

The author would like to thank **Professor Andrews** for his comments and for his input and guidance as one of the referees for this paper. The primary aim of the author in seeking to get this paper published, 14 years after it was originally withheld from publication by the UK MoD, was to provide some form of lasting record of the efforts of the unsuccessful 'Team BAe' carrier design team from 1996 to 2003, and also to provide additional background on the early days of the carrier project and some of the more interesting ideas and options that we considered. The author hopes that it will serve these purposes well.

The first point raised by Professor Andrews in his comments relates to Computational Fluid Dynamics (CFD).

The January 2003 aircraft carrier downselect decision ended the author's direct involvement in both warship design and hydrodynamics, so he can no longer claim to be fully up to date on this. Notwithstanding this caveat, the overall guiding principles on the applicability and use of CFD have not changed over the past 30 years, in spite of improvements in hardware, software and methodology. Too many in our industry wrongly regard Computational Fluid Dynamics (CFD) as being a mature and reliable field, akin to structural Finite Element Analysis (FEA), which it is not. Whilst it is perfectly reasonable for an engineer with limited training and experience to generate reliable and trustworthy structural analysis results with an off-the-shelf FEA package, without the need for experimental validation, this is still not the case with CFD, at least not for marine hydrodynamics use. CFD without experimental validation remains unreliable and potentially grossly misleading. Allied to this, CFD (unlike structural FEA) tends to be a limited and intermittent activity in ship design, and therefore a difficult (and expensive) capability to sustain in times when demand for it is low. As such it is the author's firmly held view that CFD in ship design should remain the specialist preserve of towing tank institutions and specialist university-based consultancies, who have the specialist knowledge, volume of work, experience, time and experimental facilities to generate reliable and properly validated CFD results. Shipyard design departments, warship project teams and ship consultancies themselves (as non-specialists) should overcome the temptation to acquire their own CFD tools and dabble in CFD, as the costs of building and maintaining the capability to generate reliable (validated) CFD results is generally not worth the expense, and the consequences of getting things wrong are generally too great. Shipyards and project teams that acquire their own CFD tools soon tend to find that they soon fall into disuse, or that they cannot place any degree of reliance on the results. This applies to both CFD tools for resistance & powering prediction, CFD tools for detailed flow modelling, as well as advanced 3D diffraction tools for seakeeping assessment - all are best left to specialists!

If one accepts this (i.e. that one has to go to a reputable towing tank institution for reliable CFD modelling), then it follows that one should listen to their specialist advice on whether it is best to proceed with CFD or model tests (or a combined package of both) for a given hydrodynamic task. Cost also plays a factor in this though, and in the author's experience detailed CFD studies can be almost as expensive and time-consuming as model tests, with CFD results commonly regarded as less trustworthy or robust. In the author's experience, end-customers and ship-owners generally also still prefer experimental model tests over the vagaries of CFD. Indeed, cost is (in many ways) the biggest barrier to more widespread use of CFD. In the author's view, CFD is best reserved for initial broad order comparison of hullform options, modelling of detailed flow areas that are difficult to assess in detail through experiment (e.g. around shaft 'A'-brackets) and for hullform optimisation and refinement (e.g. bow shape and bulbous bow optimisation) prior to tank testing.

Our team found that use of much-simpler regression-based (empirical) powering prediction tools, when calibrated against sea trials data for a similar hull type, and accompanied by sensible input assumptions and margins for uncertainty, gave an excellent first prediction of speed-power characteristics that aligned very well with subsequent tank test results, without having to resort to CFD. For new "slightly similar" designs of the type referred to by Professor Andrews, the author would recommend use of such a regression-based (rather than CFD-based) approach in the first instance. The author would then recommend approaching a towing tank institution and take their advice on whether CFD or model testing were appropriate for more detailed powering assessment.

In terms of Professor Andrews' paper (Andrews, 1994), this depicts very well the high level MoD preliminary design framework that we (on the industry side) operated within in the early carrier project, and the approach that MoD in-house studies followed. As industry / consultancy participants we had very little control over this framework, and even during the competitive stage were rarely given more than three or four months of 'loose rein' to work up an initial design and progress our studies, without having then to report back to the MoD with our findings and be redirected onto a re-baselined design variant or new set of cost-reduction studies. The reality was that, for all the cost-capability studies, the MoD knew pretty much what size of ship it wanted from the 1998 SDSR onwards, and steered us toward this ship size with a good degree of certainty that the allocated budget would be blown. In this regard, it would have been better for the MoD to have allowed the industry teams a longer run working up a single design variant to a greater degree of design and cost maturity, prior to downselect based on firm and fixed price bid for design and build. Alternatively, it would have been fairer and more transparent for the MoD simply to form a 'rainbow' team from the outset of the funded carrier design studies in 1999, with industry partners promoted to it (and demoted from it) according to the stage of design and their individual performance. The situation that came to pass in early 2003, whereby the winning contractor was selected through a carrier design 'beauty contest', based on preliminary cost estimates, and a design that subsequently needed to be fundamentally re-worked, without having to commit to a firm price for design and build, was both unfair to the 'losing' contractor and paved the way for the significant cost overruns that have now had to be shouldered by the UK taxpayer. Rather than delve too far into the politics on this here, please see the author's 6th November 2013 letter in 'The Financial Times' outlining his views on how things could have been done better on the both the carrier and the associated FCBA aircraft projects.

Swiftly moving on, Professor Andrews rightly highlights Eddison and Groom's (1997) paper as a key record of the early stages of the carrier project. This paper is essentially a high level (and 'sanitised') summary of the MoD's May 1997 CVF aircraft carrier concepts report, which summarised the findings and final outcome of the MoD's in-house aircraft carrier studies (as input to the 1998 Strategic Defence Review). The industry teams were provided with a copy of this MoD concepts report as 'GFI' (Government Furnished Information) at the commencement of the MoD-funded industry studies in December 1999. This formed an incredibly useful starting point for our studies, and all concerned from the MoD can be justifiably proud of this report.

As we progressed our studies, we found that emergent assumptions and constraints regarding aircraft stowage and operation, increased steelweights and scantlings associated with adoption of Lloyds Naval Ship Rules (in place of the MoD's previous 'SSCP 23' structural standard), movement to more generous accommodation standards (4-berth vs 6-berth cabins), and over-zealous interpretation of requirements by specialists and former-Royal Navy personnel on our team resulted in ship designs that were somewhat larger and more costly (for a given aircraft capacity) than the MoD concepts. To some extent this 'requirements creep' and over-specification could (and should) have been pushed back on and resisted more firmly, as it undoubtedly resulted in carrier designs that were larger, more costly and carried higher risk than should have been the case. The fact that we were in a design competition, and that MoD requirements for the ship were high level, comparatively loose and open to interpretation, did not help this any. On reflection it would have been better for the MoD to be firmer from the outset on requirements and budget for the ships, rather than leaving it to the industry teams themselves to adjudicate on the interpretation of requirements.

As regards similarity of the final Queen Elizabeth Class (QEC) carrier design and our 'losing' design, the first thing the author must stress that he has not had any detailed visibility of the final QEC design, nor indeed any of the preceding Thales designs, other than what has been openly published. Whilst the papers by Harris *et al* (2009) and Knight (2009) provide some background on the Thales designs, they are limited in the level of detail to which they go, making it difficult for the author to comment in detail on differences between the two teams.

Notwithstanding this, in early March 2003, in the immediate aftermath of the downselect decision, the author (acting on direct instruction from BAE SYSTEMS) attended at the Thales carrier design offices in Bristol and handed over all our team's hydrodynamic work, requirements decomposition and design information onto Mr. Harris of the 'winning' Thales team (lead author of Harris *et al* (2009)). Allied to this, two of the author's hydrodynamics team transferred to the Thales team, as did the marine engineer who had been heading up detailed design of our twin shaftline arrangement (Mr Sears, co-author of Harris *et al* (2009)), also our team's two most senior platform design managers. The author would therefore like to think that there was some cross-pollination from our 'losing' design (including our requirements decomposition work and our approach to key issues, as well as design features) onto the 'winning' Thales design.

It is clear (Knight, 2009) that the 'winning' Thales design went through several design iterations in the years after the 2003 downselect decision, in an attempt to contain cost and reduce risk. Although the overall visual style and appearance of the BMT/Thales design did not change, features and detail of it most certainly did (see Knight (2009) and Harris et al (2009)), which seem to have brought it closer (in content, if not visual appearance) to our 'losing' carrier design.

During our post-downselect discussions senior members of the Thales / BMT team flatly refused to entertain any notion of moving to our highly flared above water hullform; perhaps understandably, as this would have fundamentally changed the style and appearance of the 'winning' design to something approaching our 'losing' design !

Whilst the underwater form of our team's carrier design was based on a refined derivative of the 'Invincible' class hullform, Harris et al (2009) indicate that the hullform of the Thales QEC design was based on past ocean liners. Unlike the modern cruise ship underwater form that our team considered (and rejected), which was designed for a comparatively low ship speed and appeared to be significantly optimised toward maximising space for standardised cabins, the traditional ocean liner-type forms considered by the Thales team would have been optimised for higher ship speeds (traditional liners being a form of transport rather than a means of recreation). The author's understanding (based more on anecdote than hard evidence) is that such liner-type forms (typified by the RMS Queen Mary of the 1930s and the Queen Elizabeth II of the 1960s) share a common ancestry with the aircraft carrier underwater form that we adopted (whose ancestry could be traced back via the 'Invincible' class and HMS Hermes to the battlecruiser and carrier forms of the 1920s and 1930s). As such, the author doesn't believe that the rival Thales and BAE SYSTEMS designs were that far apart in terms of underwater form design.

Both team's designs featured a bulbous bow, which at the time our studies was something of an innovation for a front line Royal Navy warship and aircraft carrier. Ultimately the Thales design evolved from a 'swan neck bulb' (similar to ours) to a cylindrical bulb design (see Harris *et al*, 2009). However, the author suspects that the real life hull resistance benefits of a cylindrical build over an equivalent (fully optimised) 'swan neck' bulb are marginal – the main benefit is ease of fabrication (less double curvature plate).

In terms of other hydrodynamic features, it is evident (Harris et al, 2009) that the twin shaft element of our hybrid shaftline arrangement was carried through into the Thales design in place of their all-podded arrangement, albeit with separate motor rooms for each shaft. Had our team's design been successful, the author believes that we too would have come under pressure to eliminate the single pod of our design. In that event, the author's preference would have been to substitute a third conventional shaftline in its place. The resulting triple 'conventional' shaft arrangement (with motors for the two outboard shaftlines located in the same longitudinal compartment, so as to achieve shaftline symmetry (for produceability reasons), and a separate motor room for the centreline shaft for survivability reasons), would have avoided the high propeller loading of the twin shaft arrangement finally selected for the Queen Elizabeth carrier, mitigating noise and vibration risk. Contrary to what our team's survivability specialists indicated back in 2001 / 2002, the author doesn't believe that a triple shaftline arrangement would have been that unacceptable from an underwater signatures point of view (noting that aircraft carriers have a pretty unique infrared signature anyway during aircraft operation, are pretty horrendous from a radar cross section standpoint, and a carrier flotilla is arguably pretty easy to spot by satellite or through passive electronic warfare). Had it been the author's call, the carrier design presented in this paper (and indeed QEC) would have had a triple conventional shaftline arrangement. Or (had we wanted to be innovative) twin conventional shaftlines for cruise and one or two waterjets for boost up to maximum speed, noting that high carrier speeds are generally only required in calmer conditions where waterjet performance would be reasonable. However, the author's view is that a triple shaft arrangement is the best all-round solution for this size and speed of warship. The modest cost 'delta' of a triple shaft arrangement compared to a twin shaftline arrangement was (in the author's view) more than offset by the reduction in technical risk (re: reduced propeller loading), produceability and survivability benefits.

Early on in our studies we firmly concluded that two pairs of retractable fin stabilisers were the most appropriate solution for the carrier, as a motions-critical vessel, in spite of concerns regarding their shock survivability and cost pressure to move to a single pair. Harris et al (2009) noted that the MoD imposed such a solution onto the Thales design, possibly based on our team's work.

In terms of ship speed, the author understands (from open source data) that the design speed for the final Queen Elizabeth carrier aligns with that derived by our team back in 2002 for CTOL operations (which in turn was just one knot higher than what we concluded was necessary for STOVL operations). At the outset of the industry studies the presumption was that the carrier would have a significantly higher maximum ship speed, comparable to the 'Invincible' class. However, the 'Invincible' class were in many ways Marine Engineers' ships, with a high maximum speed, once-novel gas turbine propulsion system, huge amounts of space given over to gas turbine uptakes and downtakes, and dedicated machinery removal lifts that compromised hangar stowage space for aircraft. Our team recognised early on that the high speed of the 'Invincible' class was only achieved at some compromise to the ship's core aviation function, and that challenging the presumption of high maximum ship speed was key to minimising cost and risk of the new carriers, and maximising space available for the ship's primary (aviation) role. We therefore played a key role in challenging this presumption and bringing ship speed down to more modest levels. The author was a keen advocate of progressing with a maximum ship speed as low as 23 knots, as a way of saving cost (long, slow ship vs short, fast ship). However, this proposal was considered too challenging of expectation by our team's management, and so (for our carrier designs) we settled on a maximum ship speed somewhere in the middle (between these extremes). This modest (but nonetheless reasonable) maximum ship speed seems to have been carried forward into the final Queen Elizabeth carrier design.

The author's involvement on the BAE SYSTEMS team carrier design studies extended beyond hullform and hydrodynamics, and he would therefore also like to comment on some of the broader similarities and differences between the BAE SYSTEMS and Thales design offerings:

For our final 2002 carrier designs, our team switched from the WR-21 based gas turbine propulsion plant of our earlier carrier designs, to a Marine Trent-based gas turbine propulsion plant (with supplementary diesel generators). A similar arrangement seems to have been adopted on the final Queen Elizabeth carrier design. The author's view, having been involved on the periphery of our team's marine engineering studies from 1996 to 2003, was that the WR-21 based solution, with its smaller power units, was a neater fit for the carrier, that would have provided a well-distributed and redundant propulsion plant, beneficial commonality with the Type 45 Destroyer fleet, and allowed greater effort to be devoted to dealing with the 'teething troubles' of the WR-21 engines.

From the earliest days of the British Aerospace PV-funded studies (1997 onwards, well before the involvement of Thales in the project), our team recognised the potential of modern shoreside warehouse stores handling systems for automating handling and stowage of the large quantities of air weapons onboard the new carriers, and the significant reduction in crewing levels that this might achieve. Cdr Kevin Donnelly (RN, rtd.) of our team opened up the early dialogue with equipment vendors on this, and over the course of the next six years progressed things into a baseline automated air weapons handling proposal that is now a feature of the final Queen Elizabeth carrier design. Similarly, other aviation design features of the final QEC design, such as the 'Flyco' (Flying Control Room) configuration, bear uncanny similarity to our team's proposal. Less obvious, our aviation team also played a key role in progressing and resolving a number of key design issues relevant to the new carriers and clarifying thinking on key areas of design policy. In his January 2003 speech to UK Parliament announcing the carrier downselect decision in favour of Thales / BMT, then Secretary of State for Defence Geoff Hoon indicated that aviation design was an area of weakness on our team's design. He was wrong and did the members of our aviation team a grave injustice in suggesting this.

To conclude the discussion on similarities and differences between the Thales and BAE SYSTEMS designs, the author would like to touch on the important issue of island superstructure design. In general, the island superstructure represents an obstruction and impediment to aviation operations and there is therefore a tendency to favour the smallest possible island footprint and size. In the case of a nuclear powered carrier (where there are no main engine uptakes), or a conventional steam or diesel-powered carrier (where uptakes are of comparatively low diameter, low allowable bend radii, and consequently easy to route), this means that the optimum island arrangement is a single island superstructure, as typified by USS Enterprise (CVN-65), HMS Hermes (1959) and HMS Ocean (1998). However, for carriers with gas turbine main propulsion, the uptakes are of much larger diameter, restrictions on uptake bend radii are more onerous, and the space consumed in trying to route gas turbine uptakes together from the separated machinery spaces (required for survivability) is huge. Thus it is difficult to route the uptakes into a single superstructure with gas turbine main propulsion. The end result, if one tries to do this (unless one resorts to cascade bends, as we did on our earlier designs), tends to be a very long superstructure, as typified by HMS Invincible (1980). Consequently, our team concluded that the optimum solution for the new carriers (as gas turbine powered ships) was:

- a comparatively short main island superstructure up forward, fitted with a single funnel for the forward machinery spaces;
- a standalone and minimally-sized broad-based 'mack' (i.e. a combined mast and funnel stack) sited further aft, just big enough to accommodate the uptakes for the after machinery spaces and provide an access stairway beneath deck.

This solution, shown in Figure 15, was somewhat different to the two larger island superstructures of the Thales and final QEC designs. For our final 2002 design iterations, our aviation team proposed a 'bridge' between our main island and the 'mack', in order to generate extra superstructure space without compromising flight deck parking, resulting in the arrangement shown in Figure 1 of this paper. The author never really liked this arrangement, and remains of the view that the optimum arrangement for the new carriers would have been a short fwd main island supplemented by a standalone broad-based 'mack' further aft, as shown in Figure 15.

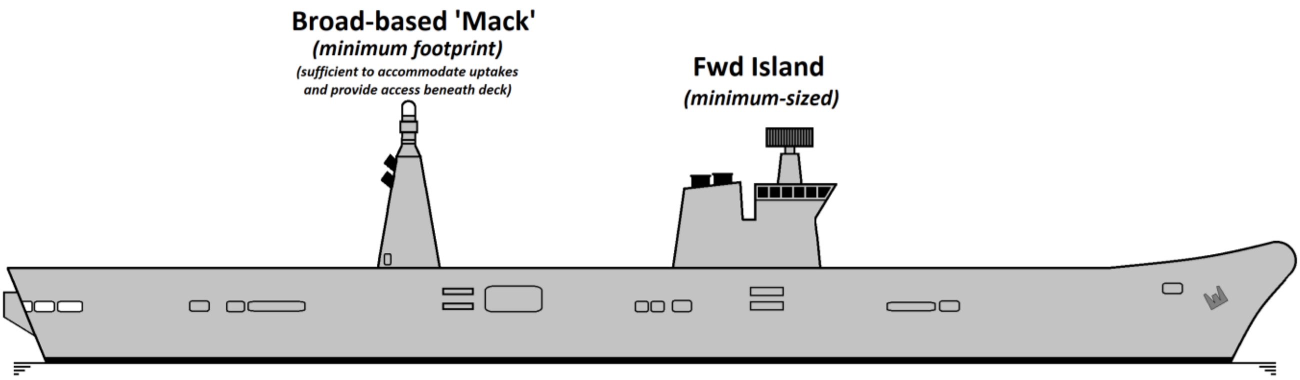


Figure 15: Optimum island Arrangement for a Gas Turbine-Propeller Aircraft Carrier (Author's opinion)

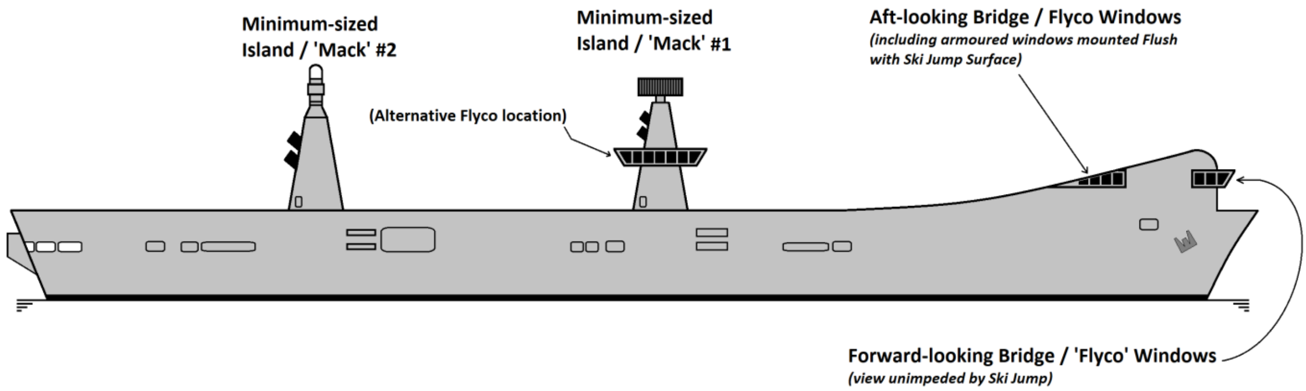


Figure 16: Large Exit Angle Ski Jump Concept for STOVL and STOBAR Carriers (Bridge and 'Flyco' located beneath Ski Jump)

The author also observes that our team's carrier designs all had 'tumblehome' island superstructures (i.e. sides tapering inwards with height above the flight deck), whereas the Thales island design flares outwards with height above deck. Whilst the Thales approach provides additional space in the island for a given flight deck footprint, our inward-flared island avoided re-entrant angles at the flight deck and is therefore better for radar cross-section (RCS). That said, side lift openings and flight deck activity ensure that the RCS characteristics of an aircraft carrier are less than ideal, in any case.

Input from our colleagues at BAe (Warton) during our early PV-funded carrier studies indicated that (for STOVL and STOBAR carrier variants) there might be significant benefit (in terms of aircraft performance) of proceeding with a large exit angle ski jump (around 20° exit angle rather than the 12°- 14° exit angle typical of existing carriers). However, the problem with such a high exit angle is that the ski jump becomes very tall (around three or four decks tall, as the author recalls), which limits view from the ship's bridge. As a potential solution to this, the author proposed relocating the ships bridge from the island superstructure to a position beneath the ski jump. Under this concept (Figure 16 below), 'Flyco' (the Flying Control Room) would also have been relocated alongside or beneath the ski jump (with aft-facing armoured glass / protective grilles for rear visibility), the main island would have been reduced to a 'mack', and the after machinery spaces would have exhausted either through a second 'mack' or directly overboard through the ships stern. An innovative proposal that was too adventurous to be considered in any detail!

In terms of the side openings that Professor Andrews refers to on the 'Invincible' class, the author's understanding is that the openings that he is referring to are the large air intake plenums (extending over two deck levels sited comparatively low in the hull, immediately abreast the hangar). Ingress of green seas through these openings would have represented a down-flooding risk, and (in spite of the separation arrangements in the plenum) could also have interfered with the operation of the gas turbines. We were aware of this issue and did attempt to assess the risk of this in our early studies. However, the reality was that our intakes were sited much higher in the hull (immediately below the flight deck or in the island, depending on ship design) and closer to midships. As such, they were sited as high as practicable above the waterline in a location where the risk of green seas ingress was minimised. Although (as ever) it is possible to conceive of 'extreme weather survival' scenarios where green seas could have entered these openings, the onus under these scenarios fell on the marine engineers to ensure that the engines could continue to operate (e.g. through appropriate filtration / water separation arrangements) and on those undertaking the stability analysis to model them as unprotected (down-flooding) points. There were (of course) other openings in the hull sides of our carrier design, in particular boat and mooring recesses. However, it was accepted that these would be out of bounds in extreme weather, and they (and their fittings - doors, tank vents, etc) would have been in full compliance with civilian freeboard and UK naval / load line requirements.

Professor Andrews makes an interesting point regarding the similar internal space but significantly different displacements of HM ships Invincible and Hermes. Steel weight typically represents something approaching 40% - 50% of the displacement of an aircraft carrier. Much of this weight difference is therefore likely to be down to Invincible having more optimised (lighter) scantlings than Hermes (whose build originally commenced in World War II where heavier scantlings and some armour was the norm). Additionally:

- Hermes' flight deck was strengthened for the more challenging loads of CTOL (vs STOVL) aircraft operation;
- Invincible (with its clean sides) lacked the hull sponsons fitted to Hermes, which would have significantly added to steel weight;
- Hermes had a much larger air group capacity than Invincible, meaning much denser outfit (2,100 vs 1,540 crew) and greater variable load (air weapons, aviation fuel, etc);
- Hermes' steam propulsion plant would have been significantly heavier than the aero-derived gas turbine propulsion plant of Invincible;
- Invincible had a shorter hull (but a much larger island superstructure) than Hermes.

In the author's view, waterline length is a more reliable baseline comparator than displacement for aircraft carrier designs. As part of our team's early studies, the author undertook a detailed trendline (scattergram) analysis of aircraft carrier design characteristics (dimensions, aircraft capacity, crew and payload) for existing and past aircraft carrier designs, and this amply demonstrated this point. Such trendline analysis is easy to do using tools such as MS EXCEL and open source warship data, and so long as one ensures that they are informed (rather than constrained) by the trends indicated, and accepts that unreliable data and scarcity of data can skew the analysis, then this is an extremely valuable tool for validating and estimating required design dimensions and parameters. Potentially the basis for another paper !

The author tends to leave the hocus-pocus of structural design and analysis to others, whilst keeping an interested and watchful eye on the overall outcome and any high level issues that it unearths. In the case of the carrier designs presented in this paper, the preliminary structural design and analysis was undertaken by structural engineers from BAE SYSTEM's Barrow-in-Furness shipyard. The results of this quite extensive assessment did not (as the author recalls) highlight any concerns (as raised by Professor Andrews) regarding stiffness of the hull girder; the hull (by virtue of its depth, many decks and very wide, thick, flight deck) was found to have more than adequate longitudinal bending stiffness. Instead, the key structural concerns were:

- The comparatively high location of the neutral axis in the hull, due to the disparity in width between the above water form and below water form (74m flight deck width vs 40m Waterline Beam) and the comparatively heavy flight deck scantlings in comparison to the keel plating. The result was high keel stresses in hull bending scenarios, with a particular concern being the risk of buckling of the hull bottom plating in hull girder hogging scenarios;
- The structural discontinuity caused by the large hull side lift openings. As with most modern large carriers, these side lift openings were situated close to the points of maximum hull girder shear force and bending moment (Figure 17). In particular, the location of the after side lift openings being close to the point of maximum hull shear force was a key concern, as the sideshell and hangar side longitudinal bulkheads are key contributors to the shear strength of the hull girder.

Our team's advisor, the late Professor Louis Rydill, played a key role in highlighting these concerns to us at an early stage, based on his experience with the cancelled Royal Navy CVA01 aircraft carrier of the 1960s. As with most structural issues, there was nothing insurmountable in these two issues, nothing that couldn't be resolved through routine structural design and judicious reinforcement / compensation details, but they were nonetheless key issues that were best addressed from the earliest stages of design.

In terms of the author's comment regarding the "relatively light structural scantlings" of the 'Invincible' class, this is based on the following:

- Steelweight estimates for our team's earliest carrier designs were based on extrapolation of scantlings of the 'Invincible' class to our hull, using the MoD 'Shipstruct' software. A short time later we commissioned QinetiQ to perform a comparison of our estimated steelweights against data that they held for other aircraft carriers, which highlighted that our steelweights were well below norm (by several thousand tonnes). This lead to a fundamental re-evaluation and upward increase in our steelweight estimates. The conclusion from this work was that 'Invincible' class had scantlings significantly lighter than other aircraft carriers;

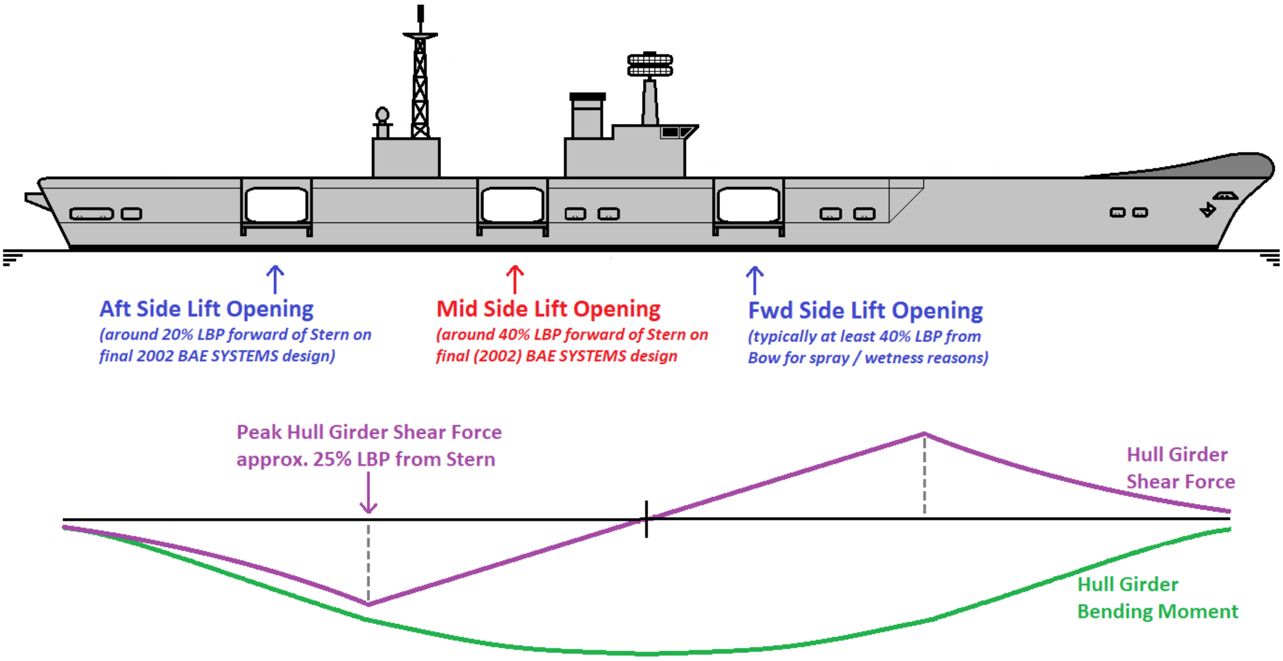


Figure 17: Generic Aircraft Carrier Profile, showing the Location of Aircraft Lift Sideshell Openings relative to Positions of Maximum Hull Girder Shear Force and Bending Moment

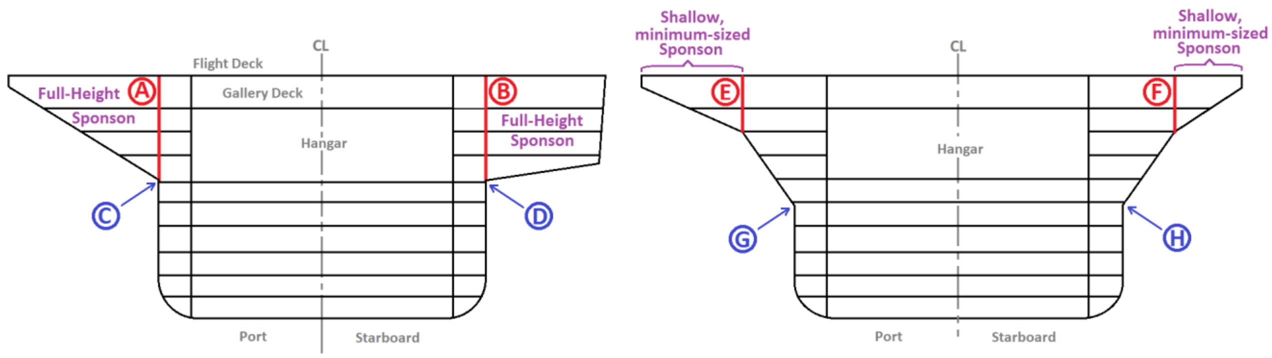
- When we re-baselined our steelweights based on the (then newly issued) Lloyd's naval ship rules, we found that minimum allowable steel thicknesses (specifically deck thicknesses) were in excess of the thicknesses of the 'Invincible' class. Due to the size and internal volume of our design, the resulting (modest) increase in required deck thickness had a significant effect on steelweight;
- During a visit to a large US Navy aircraft carrier in April 2000, it became apparent that the subdivision and thickness of the steel was far in excess of comparable structure and subdivision of the 'Invincible' class;
- During a visit to one of the 'Invincible' ships at sea in the late 1990s, a senior officer attributed the vibration experienced when the ship accelerated to the hull being design to light "cruiser scantlings", optimised for higher ship speed, as opposed the heavier scantlings of previous carriers.

This is not to say that the scantlings of the 'Invincible' class were in any way inadequate – just that they were lighter and more optimised for higher speed.

Professor Andrews requested further justification of the author's assertion that our highly flared above water form simplified internal structural arrangement 'by eliminating of the need for a longitudinal bulkhead'. To clarify this, the author refers to Figure 18. With the traditional (sponson) style of above water form (Figure 18(a)) the sponsons typically extend vertically over the entire depth of the Hangar. Moreover, the junction of the sponsons with the hull (Points C & D of Figure 18(a)) represent a fundamental discontinuity in shape. Consequently, to maintain structural continuity:

- Longitudinal bulkheads (effectively the vertical continuation of the main hull sideshell) are required as indicated by 'A' and 'B' of Figure 18(a), extending over the full depth of the hangar. Without this, load transmittal paths become complicated.
- Structural compensation is required at locations 'C' and 'D' of Figure 18(a).
- Any opening in bulkheads 'A' and 'B' (or removal of them) requires significant compensating detail to ensure adequate load transmittal to (and within) the main hull.

With the highly flared style of above water form, the transitions indicated by points 'G' and 'H' of Figure 18(b) are gentle, avoiding the need for excessive reinforcement at this location. Although small (shallow) sponsons are required on the upper part of the hull to adjust the post-flare upper reaches of the hull to match the local flight deck width, these sponsons are far smaller than with the traditional style of above water form. Thus, although small longitudinal bulkheads (or other form of support, such as pillars) are required at 'E' and 'F', as indicted in Figure 18(b), these are far smaller and lighter than the corresponding full depth bulkheads ('A' and 'B') required by the traditional style of above water form. As such, the author stands by his comment that the highly flared style of above water form is simpler and neater structurally. As ever, there is more than one structural arrangement possible with either option, but (hopefully) looking at Figure 18 the reader will see that the highly flared above water form is more elegant (both structurally and aesthetically) than the traditional (sponson) style of above water form.



(a) Traditional (Sponson) Style of Above Water Form (b) Highly Flared Above Water Form

Figure 18: Differing Structural Layout of the Traditional (Sponson) and Highly Flared Styles of Above Water Form

From our team's earliest carrier concept design (our May 1998 PV-funded 40 STOBAR carrier design) onwards, our team employed a highly flared above water form, and no formal structural comparison was undertaken between the highly flared and conventional 'sponsoned' styles of carrier above water form. There was no need, it was a top level decision regarding the style of our design. To us the highly flared approach (i.e. using flare to accommodate as much of the disparity between waterline beam and overall (flight deck) beam as possible, and then using small (shallow) sponsons to accommodate the remaining disparity), was by far the most elegant solution. Our team's structural design work demonstrated that an efficient hull structure compliant with Lloyds Naval Ship rules could be achieved with the highly flared above water form, and data provided by Qinetiq indicated that our resulting hull steelweights were not excessive. Our team's considered view, based on based on 4 years of assessment, was that the Highly Flared Form was better spatially, for structural simplicity, from a build perspective and less likely to experience structural problems through-life (re: structural continuity). In the author's view, the sponsons of the Thales design and US aircraft carriers are a throwback to the major upgrade and retrofit of angled runways to axial deck carriers in the 1950s, rather than an elegant solution for a newbuild 21st century carrier. Aside from the move to nuclear propulsion, the US Navy has followed a largely evolutionary approach to carrier design since the first 'Forrestal' supercarrier of the 1950's and are pretty much tied to continuing with the sponson-based approach of the 'Nimitz' class, due to the prohibitive cost of moving away from this existing legacy design – not the case for our totally new carrier design. In terms of infrastructure, fundamentally re-worked / all-new infrastructure has been required for our new carriers in any event (including re-working of existing drydocks and construction of extra-wide harbourside pontoons), even with a sponson-style of above water form, so this is not a fair discriminator between the two styles of above water form.

Our team's highly flared above water form was part of a broader strategy of attempting to minimise the need for ad hoc (local) sponsons extending beyond the basic envelope of the main hull. In the case of STOBAR carrier variants, a novel proposal from the author during our team's early studies, similarly intended to minimise the need for sponsons, is as shown in Figures 19 & 20 (never progressed beyond initial concept). This would have eliminated the large Port-side sponsons more traditionally associated with STOBAR carriers (Figure 21), by obviating the need for an angled runway. Instead, under this novel proposal, a hinged / retractable ski jump would have been fitted to the ship, to allow use of the ship's axial launch runway for STOBAR aircraft recovery. As this concept remains a potential means for facilitating STOBAR operation of conventional carrier aircraft (e.g. F/A-18 E/F Super Hornet) from the new carriers, with only relatively modest modification to the ships, the author encloses the sketches of Figures 19 & 20 as a record of this concept.

One further point that the author would like to make, concerns hangar and side lift configuration:

All carrier designs produced by the BAE SYSTEMS team aligned with established US carrier practice, in having a single level (tall) hangar. The hangar height, as driven by Merlin helicopter maintenance (rotor head removal) requirements, resulted in a hangar far in excess of that required to simply stow F-35 fixed wing aircraft. Significantly increased F-35 aircraft stowage would have resulted had a twin level hangar been adopted (see Figure 22). This could have been achieved without significantly increasing hull depth, had it been accepted that helicopters could only be stowed and maintained in one (taller) part of the hangar, or had movable / removable decks been considered, or had the gallery deck (above the hangar) been deleted from the design. The post-war 'Audacious' class carriers of the 1950s and some preceding World War II Royal Navy carriers featured such a twin level (or partial twin level) hangar. With each F-35 aircraft for the new carriers costing in excess of £75M, and equipped with specialist stealth coatings and sensitive electronics, the scope that such a twin-level hangar would offer for stowing the entire air group below decks during lengthy, low-risk transits (rather than around 30% - 50% of the air group having to be stowed in the open on the flight deck, exposed to the elements) is attractive. Clearly a second Hangar deck could also have served a useful secondary purpose as a stores / equipment stowage area when acting in humanitarian relief and amphibious roles. Also, as demonstrated by HMS Ark Royal IV (1955), whose lower hangar was successively converted to other purposes during the life of the ship (leaving just a partial-length lower hangar later in the vessels life), a twin hangar configuration provides a useful space margin for future conversion. Unfortunately, although highlighted as a possibility in the MoD's in-house studies for the new carrier (Eddison & Groom, 1997), there was no appetite to explore this option during our industry studies. In many ways, this lack of due consideration of a twin-level hangar option was a missed opportunity. Yes, the increased hull depth would likely have increased draught, but the base porting and infrastructure issues around this were not insurmountable.

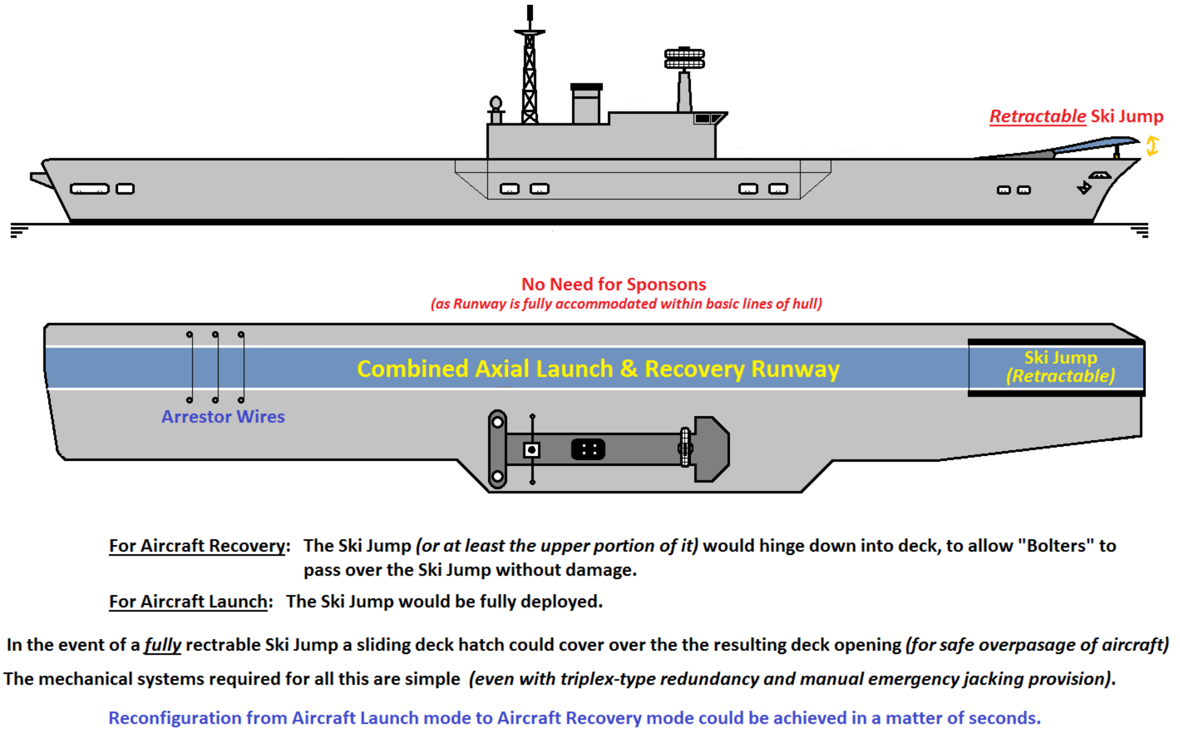
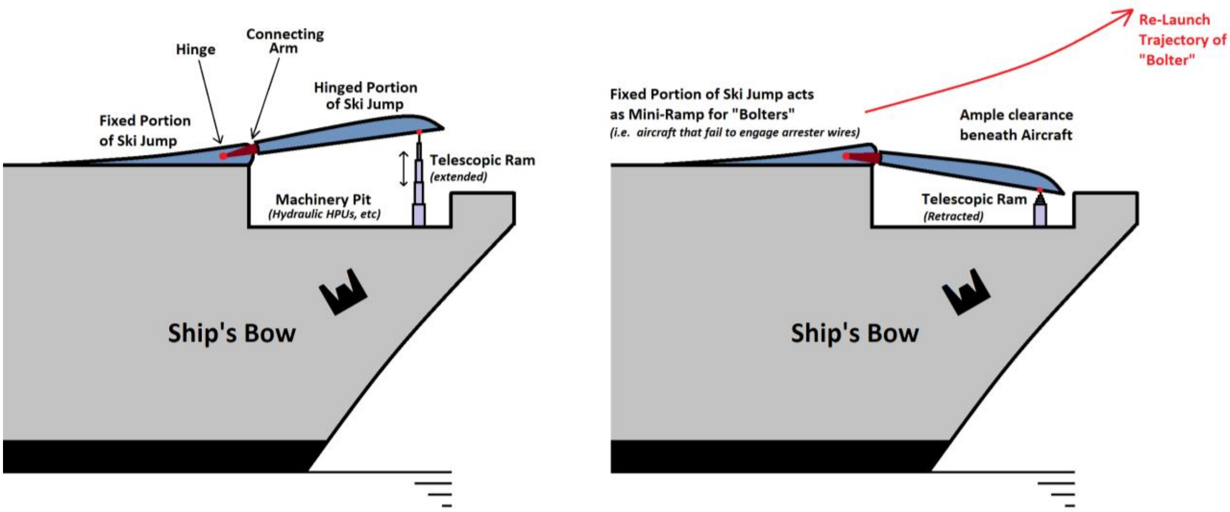


Figure 19: Author's Proposed Novel STOBAR Aircraft Carrier Configuration (based on a Combined Axial Launch & Recovery Runway and a Hinged / Retractable 'Ski Jump' Launch Ramp as per Figure 20 below)



(a) Ramp Fully Deployed (for normal Aircraft Launch Operations)

(b) Ramp Retracted (during Aircraft Recovery when there is a Risk of "Bolters")

NOTE: The relative lengths of the fixed vs retractable portions of the Ski Jump would be determined by allowable undercarriage loads. The entire ramp could be made retractable if needs be.

Figure 20: The Author's Proposed Concept of a Retractable Ski Jump for STOBAR Aircraft Carriers

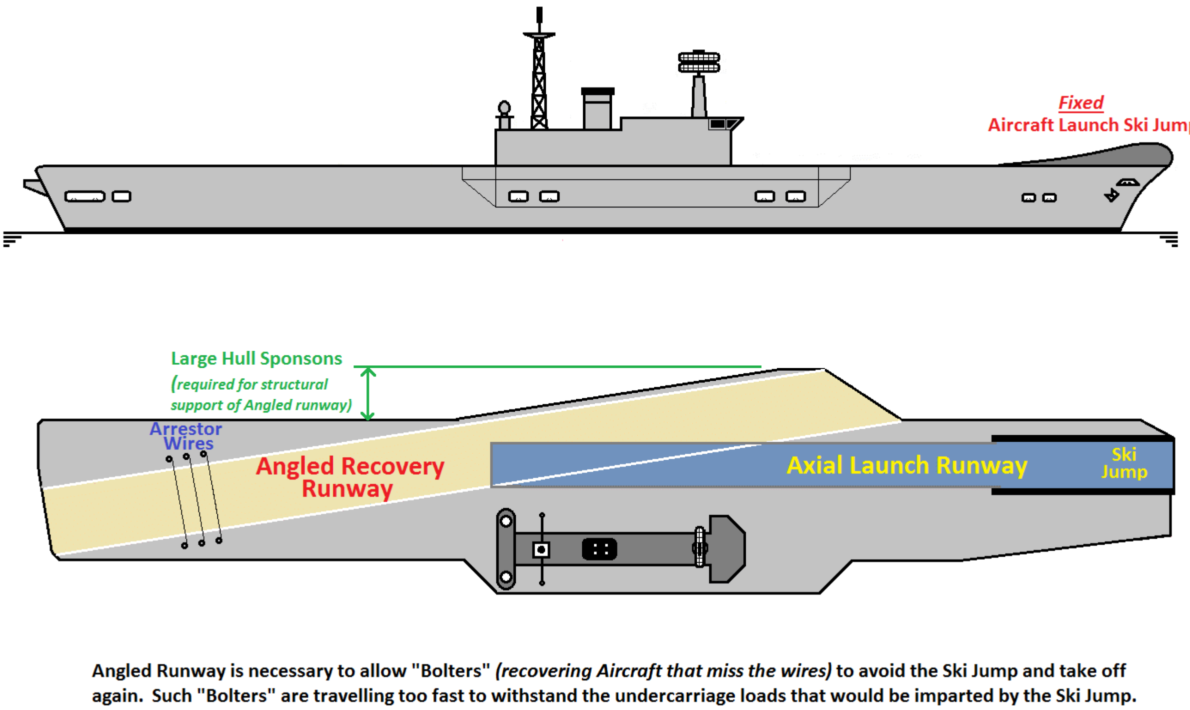


Figure 21: More Traditional Configuration of STOBAR Aircraft Carriers (as per current Russian, Indian & Chinese Aircraft Carrier practice)

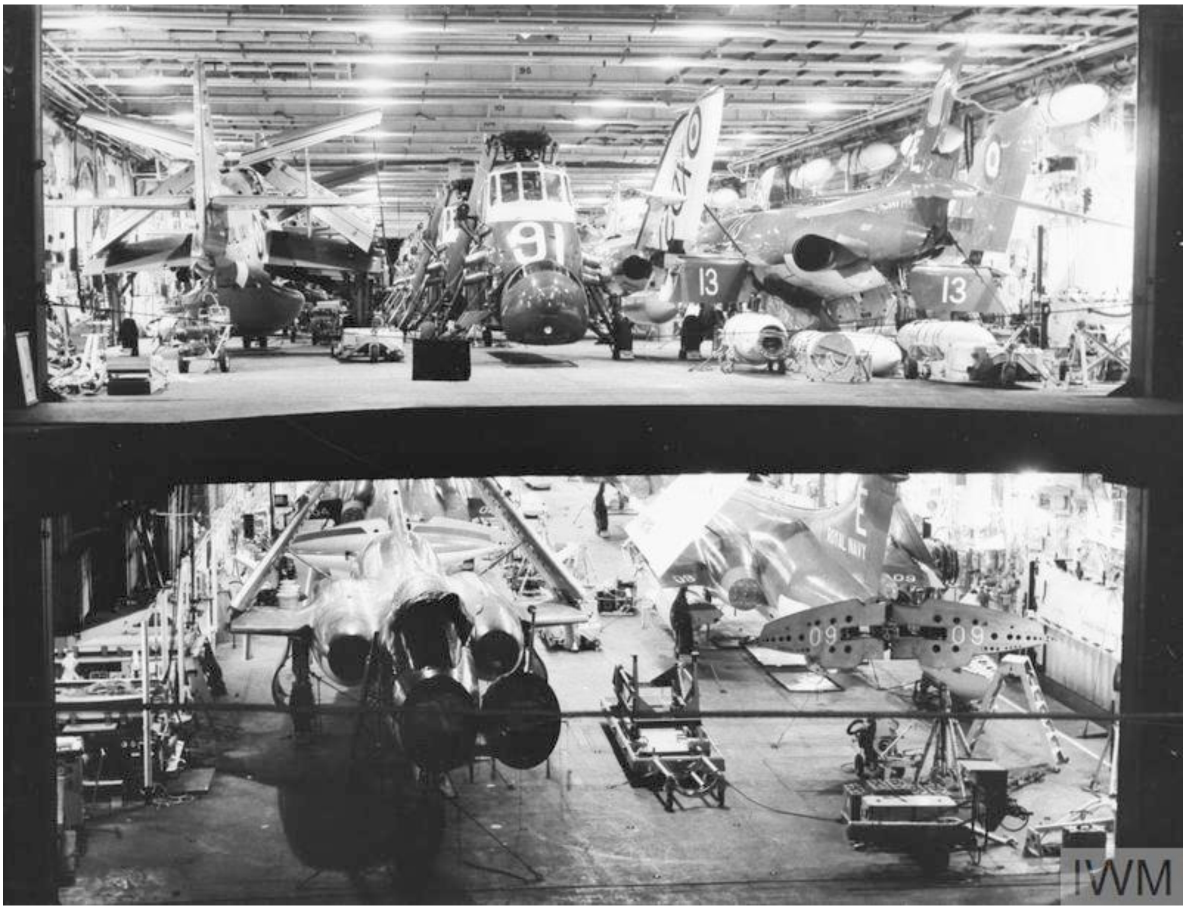
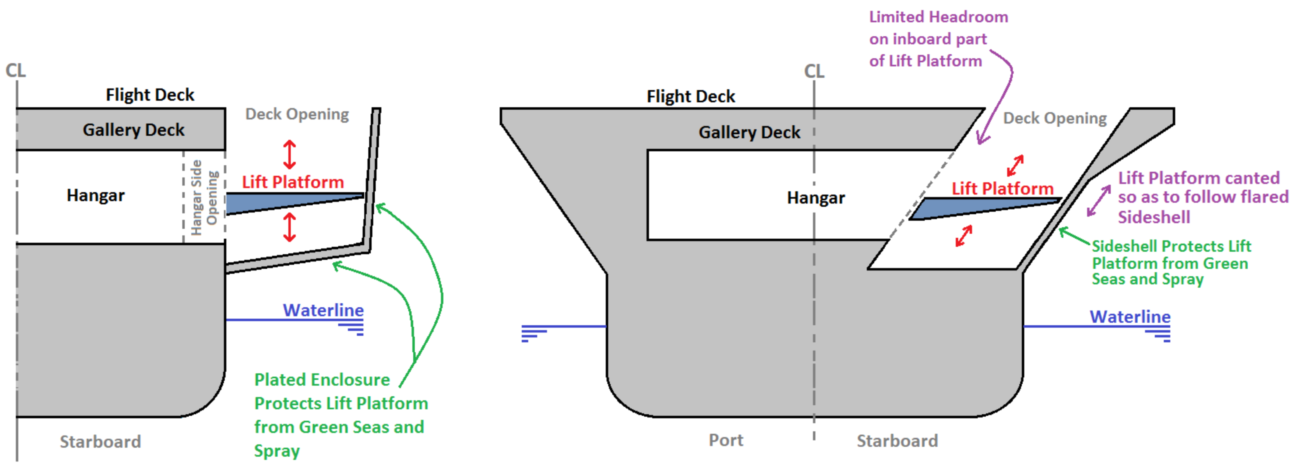


Figure 22: The Twin Level Hangar Arrangement onboard Royal Navy 'Audacious' Class Carrier HMS Eagle (1965) © UK Imperial War Museum / UK Crown Copyright, Source: www.iwm.org.uk/collections/item/object/205164866

From the start of the MoD-funded studies, our designs mirrored US practice by employing side lifts (rather than inboard lifts) for transferring aircraft between the hangar and the flight deck. The use of such open (exposed to the elements) side lifts dates from the immediate post-war years where naval aircraft were much lower cost and where occasional aircraft loss / damage was tolerated. Whilst the likelihood of lift platform immersion and spray were minimised in our design, the reality is that ship motions and sea states are random in nature. In the modern era, where naval aircraft cost in excess of $100M a piece, it is arguable that aircraft deserve greater protection from the green seas and spray during lift transfer to and from the flight deck. Although inboard lifts offer such protection from the elements, they are undesirable due to the impediment they impose on flight deck operations. One novel solution therefore proposed by our team was to 'plate-in' the side lifts, as shown in Figure 23, so that they become fully enclosed and protected from the elements (i.e. effectively become an inboard lift located hard-up against the sideshell). With the highly flared hullform, such an 'enclosed' side lift would be canted so as to follow the sideshell flare, resulting in some headroom restrictions on the inboard side of the lift platform. In the author's view the increased hull steel weight of this approach was justified both in terms of increased protection of aircraft, reduced vulnerability of the hangar to weapons entry, and a beneficial reduction in radar cross-section (RCS) due to the elimination of large lift openings in the sideshell. Unfortunately, as with many novel suggestions on a project of this scale, this option of enclosing the side lifts (although outwardly promising) was never progressed beyond initial suggestion.

One other noteworthy potential innovation, highlighted by the author, but never progressed by our team, was the potential use of electrically-powered boilers (in place of conventional fuel-powered boilers) to generate steam for the steam catapults of CTOL aircraft carrier variants. The marine engineers were clear that thermodynamics were not on the side of this concept, as using fuel to generate electricity via a gas turbine alternator, only to then use that electricity to generate steam is not an efficient process. Nonetheless, to the author, the idea seemed to offer potential on 'all electric' ships such as ours, in that it would avoid the need for a totally standalone fuel-based steam raising plant to be fitted for the catapults. This electric boiler concept would have integrated neatly with the ships' all-electric propulsion system, could have offered some maintenance benefits over conventional boilers, and could have been readily retrofitted to the ship part-way through the vessels life (as part of a then-proposed through-life upgrade from STOVL to CTOL operation). Developing an electric boiler for the catapults was (in the author's view) preferable to dusting off a 1950s or 1960s naval boiler design. It is easy to see how four of six of these electrically-powered boilers dotted around the ship would have been considerably easier to implement and been spatially less-demanding than a steam-raising plant based (for redundancy reasons) on two large fuel-powered boilers sited necessarily (for survivability reasons) in separate boiler rooms. In the author's view this electrically-powered boiler concept was a potentially good compromise between proceeding with a technologically immature (and consequently high risk) electromagnetic aircraft catapult launch system and the unpalatable alternative of going back to a 1960's-style catapult steam-raising plant. The American and French would not have been able to help us very much on a steam-raising plant, as their carrier fleets are now nuclear-propelled and are readily able to raise large amounts of steam (albeit 'wet' steam) from the reactor plant, without the need for fuel-powered boilers.



(a) Applied to a Traditional (Sponson) Style of Above Water Form

(b) Applied to Highly Flared Style of Above Water Form

Figure 23: Enclosed Side Lift Concept

One final point, that the author feels almost duty bound to mention, concerns the limited self-defence provision on the Queen Elizabeth class carriers. Whilst our early carrier designs incorporated a whole plethora of survivability features, and dare say all are replicated (or surpassed) on the final ship design entering service now, the best bet is not to get hit by weaponry in the first place. In this regard it is unfortunate that the self-defence capability of the new carriers seem to have been so limited by funding considerations. Our early designs allowed for 'Navalised ASRAAM' (which has since evolved into Sea Ceptor) or Sea RAM, both of which were promising and affordable defensive missile systems significantly more capable than the 'entry-level' Phalanx guns now being fitted. The author always hoped that 'hard kill' Anti-Torpedo Torpedo (shelved in the late 1990s) would be revived for the carriers, given the crew size, high value of the ships / aircraft as strategic assets, and their vulnerability to submarines. All of which could be funded by foregoing the cost of a couple of F-35 aircraft. One only has to look at the cases of Atlantic Conveyor, General Belgrano and HMS Coventry to see what fate faces large naval ships without the wherewithal to properly defend themselves against close-in threats, and over-reliant on other vessels for defence.

Finally, in closing, on a more savoury note, the author shares Professor Andrews' view that it would be worthwhile (while minds are still fresh) for there to be a paper on construction and shipbuilding strategy for the aircraft carriers, and can suggest some potential contacts who may be able to assist on this.

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Please also refer to References listed in the Paper on pages A-440-A441 of this edition.

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