SYM-AM-18-040

PROCEEDINGS
OF THE
FIFTEENTH ANNUAL ACQUISITION RESEARCH SYMPOSIUM

WEDNESDAY SESSIONS
VOLUME I

Acquisition Research:
Creating Synergy for Informed Change

May 9–10, 2018

Published April 30, 2018

Prepared for the Naval Postgraduate School, Monterey, CA 93943.

ACQUISITION RESEARCH PROGRAM
GRADUATE SCHOOL OF BUSINESS & PUBLIC POLICY
NAVAL POSTGRADUATE SCHOOL

Comparing Ship Versus Aircraft Development Costs

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Abstract

Both warships and military aircraft are highly complex, engineered products that can cost hundreds of millions of dollars each. But the development cost for an aircraft is frequently many times the cost for a ship, in some cases one to two orders-of-magnitude greater (DDG 51 development cost $3 billion, F22 development cost $30 billion). This paper first examines and compares the top-line development costs for a broad range of ships and aircraft, from commercial (e.g., passenger ships and aircraft) to military (destroyers versus fighters), using publicly available cost numbers. It then takes a deep dive into two cargo platforms, T-AKE *Lewis and Clark* and C-17 Cargolifter, using cost data from primary sources. It then compares the development expenditures for the two platforms as a function of time and products (e.g., the use or lack of full-scale models as part of the respective development processes). It finally provides a broad historical perspective to explain how these differences between ships and aircraft actually began in their original development communities during the 19th and early 20th centuries.

Introduction and Research Methodology

Both warships and military aircraft are highly complex, engineered products that can cost hundreds of millions of dollars each. But the development cost for an aircraft is frequently many times the development cost for a ship, in some cases one to two orders-of-magnitude greater. The literature on why this is the case is almost non-existent. The only published study that examines this disparity was recently carried out by RAND, appropriately titled *Are Ships Different?* (Drezner et al., 2011). It focused on the acquisition process of ships compared with that of missiles, aircraft, and tanks. The study highlighted the fact that ships are typically built in low numbers of units compared with other programs. It showed that “ship programs do not typically design and build prototype units designated solely for test,” which is almost always the case for other program types, in order to de-risk the final production run. Finally, in part because the lead operational ship acts as the de facto prototype for the rest of the class, full-scale production for ships begins at Milestone B, whereas other programs include extensive prototyping in the engineering development phase after Milestone B, before committing to full scale production at Milestone C (Figure 1).

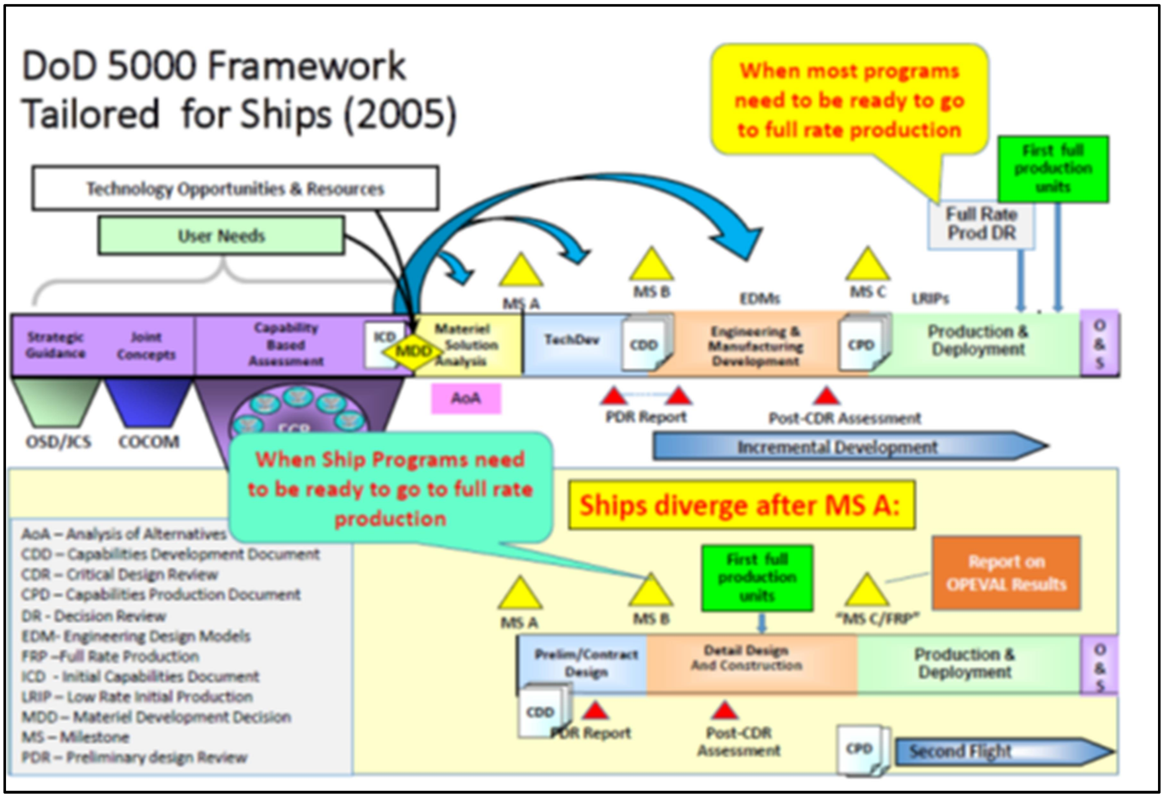

Figure 1. Ship Acquisition Timeline Compared With Other DoD Program Timelines

This RAND study highlights the need for a deeper examination of the cost disparities between the development of ships and aircraft, not only military but also commercial ones. For this reason, I first examined the development cost disparities at a high level between several different ship and aircraft programs, then took a deep-dive comparison between two cargo platforms, T-AKE *Lewis and Clark* and C-17 Cargolifter. These candidates were selected for the following reasons:

- The two platforms are broadly similar in mission: to carry cargo. This largely removes disparities between, say, multi-mission destroyers and single-mission fighters.
- The two platforms have very few weapons systems and combat systems, which can complicate the costing structures for both system development and platform integration.
- The detailed development cost data for the two military platforms are relatively straightforward to obtain via public domain sources; by contrast, detailed development cost data for both commercial aircraft and commercial vessels are proprietary and closely held by companies.

Ship Versus Aircraft Development Costs in Context

My first task was to compare a variety of ship and aircraft programs to determine if there was indeed a general trend of higher development costs for aircraft compared with ships, and to get a rough order-of-magnitude assessment of the difference between them. Table 1 shows these comparisons across both military and commercial platforms, in the United States and in the United Kingdom.

Table 1. Ship Versus Aircraft Costs as of 2005

(Ferreiro, 2016)

	UK Type 23 frigate		UK Typhoon fighter	US DDG 51 destroyer		US F22 fighter
Units	16		620	62		187
Development	**$0.7B**	34x	**$24B**	**$ 3B**	10x	**$28B**
Procurement	$4.3B		$23B	$60B		$34B
Total	$5.0B		$47B	$63B		$62B

	T-AKE Cargo ship		C-17 Cargo plane	Cruise Passenger Ship		Airbus A380 Passenger plane
Units	12		190	10		65+
Development	**$0.1B**	50x	**$ 7B**	**$0.06B**	200x	**$13B**
Procurement	$4.6B		$59B	$ 6B		$22B+
Total	$4.7B		$66B	$ 6B		$35B+

The trends show an order-of-magnitude difference between military platform (Type 23 vs. Typhoon, DDG 51 vs. F22, T-AKE vs. C-17) and a two orders-of-magnitude difference between commercial platforms (passenger ship vs. A380). This confirms that the disparity between development costs is not limited to warships and combat aircraft, but instead is a systematic trend across platform types, whether military or commercial.

Figure 2. C-17 and T-AKE

C-17 Versus T-AKE Development Costs

The next step in this study was to take a more in-depth look at the development costs between the T-AKE *Lewis and Clark* and the C-17 Cargolifter (Figure 2). The cost data was obtained from public domain sources (Defense Acquisition Management Information Retrieval [DAMIR], 1997; GAO, 1991; Naval Sea Systems Command [NAVSEA], 2017; Naval Surface Warfare Center Carderock Division [NSWC-CD], 2018; DAMIR, 2011) and is shown in Table 2. Of specific note is that for the T-AKE, the detailed design costs for production is accounted for in a separate line item that is part of Ship Construction, Navy (SCN) and not part of the Research, Development, Test and Evaluation (RDT&E) budget. By contrast, the detailed design costs for production of the C-17 is spread among the various elements included in the development costs, and cannot be readily broken out as a separate cost. Rather than follow the specific Work Breakdown Structure (WBS) for each platform, I have attempted to correlate major cost categories between the platforms where possible, and break out unique cost categories for each platform where needed.

Table 2. C-17 Versus T-AKE Research, Development, Design and Test (RDDT) Costs in $ Millions, Rounded to the Nearest $1 Million

(DAMIR, 1997; GAO, 1991; NAVSEA, 2017; NSWC-CD, 2018; DAMIR, 2011)

C-17 (1991)		T-AKE (2001)	
		Early stage designs	1
		Baseline designs	3
		Model basin testing (hull)	1
Structures (fuselage, wing, tail)	221		
Structural analysis	115	Survivability analysis	1
Power system (engines)	119		
Electrical system	26		
Avionics and flight control systems	203		
Mechanical systems (environmental, landing, control surfaces)	95	Environmental, safety and health	1
Mission equipment	11	Mission systems (cargo)	3
Other	11	Other studies	5
Test vehicle manufacturing (1 flyable test aircraft, 2 ground test airframes)	211		
Other unallocated	40		
Systems engineering, design, and integration	114	Systems integration design	6
Project management, test & evaluation, and support equipment	900	Program management and support	6
		Detailed design	120
Other unspecified, including full-scale testing of 1 flyable test aircraft and 2 ground test airframes	2,130		
TOTAL RDDT (1991)	**4,200**	**TOTAL RDDT (2001)**	**147**
Actual RDDT (2004)	6, 687		

Analysis of Development Expenditures

Major cost items for the C-17 were as follows:

- Structures, which includes development of the fuselage, wing, and tail section (Each of these was adapted to the unique short-field landing requirement of the aircraft.)
- Structural analyses of the above
- Power and electrical systems, including development of high-capacity thrust reversers for the four main engines
- Avionics (cockpit) and flight control (fly-by-wire) systems, which included the development of full-scale cockpit mockups
- Test vehicle manufacturing and full-scale testing of one flyable aircraft (i.e., a prototype) and two ground test airframes, including static and dynamic structural loading tests
- Systems integration, including mating surfaces and equipment for subsystems and major systems

- Project management, test & evaluation, and support equipment

Small-scale model testing (e.g., in wind tunnels) was not broken out directly, but is presumably included in the above items.

The actual development cost for C-17 escalated from $4.2 billion in 1991, when the detailed data for this study was generated, to $6.7 billion as of the Selected Acquisition Report (SAR) that formed the 1999 President's Budget, which showed costs out to fiscal year (FY) 2004. Therefore, the final detailed numbers for the items in Table 2 are likely to be, on average, 50% greater than shown.

For the T-AKE, the major cost items were as follows:

- Early stage design work, which included feasibility studies, point designs using computer-aided design tools, and hydrodynamics testing of small-scale models up to 10 meters long, at facilities such as the Naval Surface Warfare Center Carderock Division (NSWC-CD)
- Mission systems, including computer-aided cargo flow modeling
- Systems integration design; program management and support, which includes all of the documentation necessary to pass Milestone decision authorities; and support from the classification society American Bureau of Shipping
- Detailed design costs, including direct shipyard and subcontracted engineering to develop detailed plans for production

These cost items are current, as the ship entered service in 2006, and these numbers align with the 2011 SAR.

The most remarkable difference between the C-17 development program and that of the T-AKE is the testing. For the T-AKE, the small-scale model testing for hydrodynamics (e.g., speed-power) is on the order of $1 million. For the C-17, the full-scale construction and testing of one flyable, prototype aircraft plus two ground test airframes is about $2.3 billion, about half the total development cost for the aircraft, and also 2,300 times (three orders of magnitude) greater than for the T-AKE. Other full-scale testing included the cockpit mockups. Although other examples abound (e.g., structural analysis for the C-17 is one hundred times greater than for the T-AKE survivability analysis), it is the use of full-scale testing versus small-scale testing that accounts for the lion's share of the difference in development costs between the two platforms.

Explanations for Differences in Development Expenditures

The differences between the development costs for aircraft and ships are seen in their overall program approaches. Figure 3 highlights these differences, while Figures 4, 5, and 6 compare the activities for each at the different phases of their respective development programs. Note again (as shown in Figure 1) that ship production begins at MS B, while aircraft production begins at MS C.

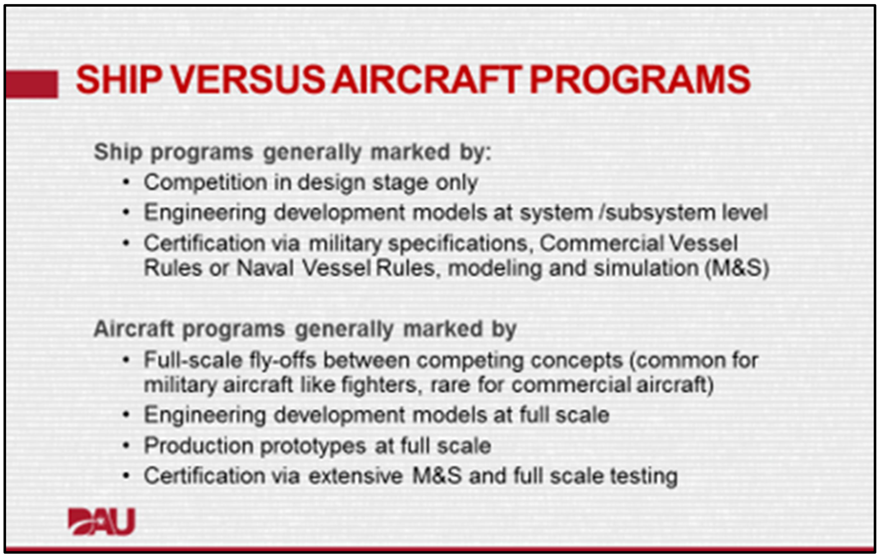

Figure 3. Overall Differences Between Ship and Aircraft Development Programs

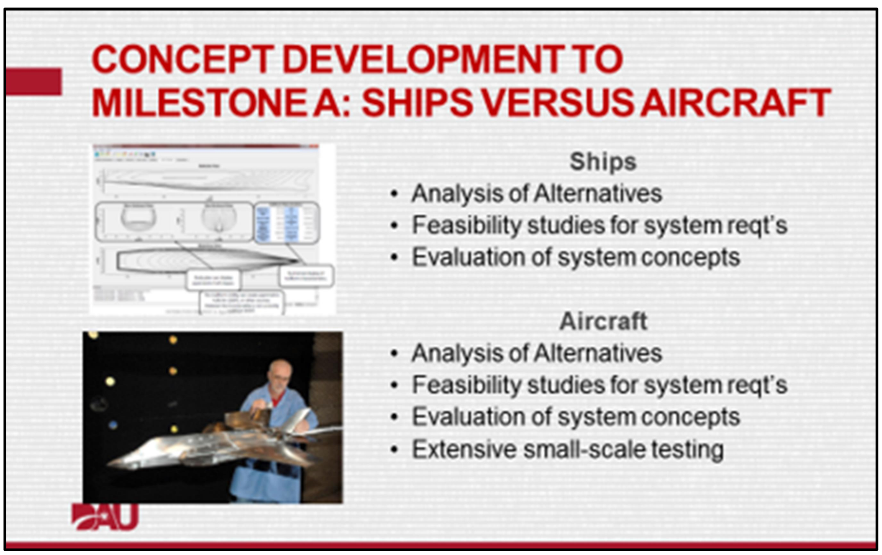

Figure 4. Differences Between Ships and Aircraft at the Concept Development Phase

Figure 5. Differences Between Ships and Aircraft at the Technology Development Phase

Figure 6. Differences Between Ships and Aircraft at the Systems Development Phase

Specific to T-AKE versus C-17, the most noticeable difference between the two platforms lies in the verification and validation processes for the designs and production models. Verification and validation of the T-AKE involves having the ship classed by the classification society American Bureau of Shipping (ABS). Classification is a process where a society like ABS develops internationally-recognized rules for design and construction of ships, which can also include national and international safety regulations (e.g., for stability). In this circumstance, ABS reviews plans and calculations done by the shipbuilder to verify compliance to design code, and regularly inspects the vessel while under construction and in trials to ensure adherence to code. In many cases, the vessel remains “in class” (i.e., the owner contracts with ABS to carry out regular surveys in service in order to ensure continuing compliance with the standards). Many warships today are also classed by classification societies (e.g., Lloyd’s Register Naval Ship Rules, Bureau Veritas Rules for the Classification of Naval Ships). In other cases, like for the U.S. Navy, shipbuilding standards and specifications are developed by the Navy itself, which carries out its own inspections. The first in-service ship is also the first one to go through the classification process, in a sense serving as a “test vessel” for the entire class.

By contrast, the verification and validation program for C-17, as explained, involves the construction and testing of many full-scale models, mockups, and prototypes for the full platform, as well as subsystems. Unlike the T-AKE program, the C-17 program developed and extensively tested full-scale cargo hold mockups, full-scale engine mockups, full-scale cockpit mockups, and full-scale wing sections, which were tested to destruction. It also had, as noted, one flyable, prototype aircraft plus two ground test airframes.

Rationale Behind Differences in Development Expenditures

We have identified full-scale prototyping for aircraft verification and validation, versus the rules-and-standards-based system for ships, as the primary driver of the difference between the costs for aircraft and ship development. The next question is, “Why should this be the case?” There are a number of myths that have been proposed to explain this, and they all fall apart upon close inspection. These myths fall under three general categories:

1. Criticality and Safety. Aircraft accidents are seen to be particularly horrific events, especially when the accident causes the plane to literally fall from the sky. A case in point is the catastrophic explosion (due to faulty wiring and poor design) of TWA 800 off Long Island, NY in 1996, killing all 230 people aboard. Thus, the need for extremely high levels of safety afforded by rigorous, full-scale testing of critical systems. By contrast, ships floating on water certainly *appear* safer than aircraft. Yet this is patently not true. In 1994, MV *Estonia* foundered in the Baltic Sea with the loss of 852 lives, about four times the number killed on TWA 800. The blame was ultimately placed on faulty design and operation of a safety-critical system, the bow doors, in part because the wave loads were underestimated—a problem that might have been avoided with rigorous full-scale testing. (Note that both C-17 and T-AKE each carry about 140 military personnel, so, in theory, they should employ equivalent means of achieving appropriate levels of safety. They do not.)
2. Number of units built. Some of the interviewees in the RAND study *Are Ships Different?* claimed that “because of the relatively high unit cost and low total production quantities, ship programs do not typically design and build prototype units designated solely for test” (Drezner et al., 2011). This is a red herring. The previous two classes of U.S. Navy destroyers were built in quantities comparable to, or greater than, those of military aircraft. The DDG 51 class has 62 units and is projected to have 77 units; the DD 963 class had 62 units, including the follow-on series DDG 993 and CG 47/52. By contrast, the F-22 fighter has 187 operational units, while the B-2 bomber has just 21 units.
3. Complexity. Aircraft are perceived to be more complex than ships, thus require more rigorous testing to iron out the bugs. Again, this is false. Using parts count as a straightforward if unsatisfactory proxy for

> complexity, the *Ohio*-class submarine, with 350,000 parts (and which is verified and validated via the same type of rules-and-standards method as surface warships) is more complex than the F-16 fighter with just 175,000 parts (Drezner et al., 2011).

There are many valid reasons why shipbuilding programs could and should incorporate full-scale prototyping as part of the verification and validation process. This will not happen, of course, so the question remains, “Why are ships and aircraft different?”

The answer lies in the origins of the modern shipbuilding and aircraft industries. In the 19th century, the same men who built iron and steel ships also constructed bridges, buildings and railroads, and both used rule-of-thumb methods and visual inspections as their means of verification and validation of designs. In the 1860s, the British engineer William Fairbairn used the same methods for calculating bridge girder loads and stresses in his foundries, as he used for building newfangled iron ships in his shipyard. He even used the same factors of safety for structural loading. Those methods were carried on by the many steelyards in the 20th century that also built ships, such as the Missouri Valley Bridge & Iron Co., which constructed more LSTs (Landing Ship, Tank) than any other yard in World War II. This civil engineering inheritance is especially noteworthy when comparing the aforementioned ABS rules with civil building codes (Figure 7). For this reason, RAND was correct when it noted that “Ships are more like a major military construction project than weapon-system procurement” (Drezner et al., 2011).

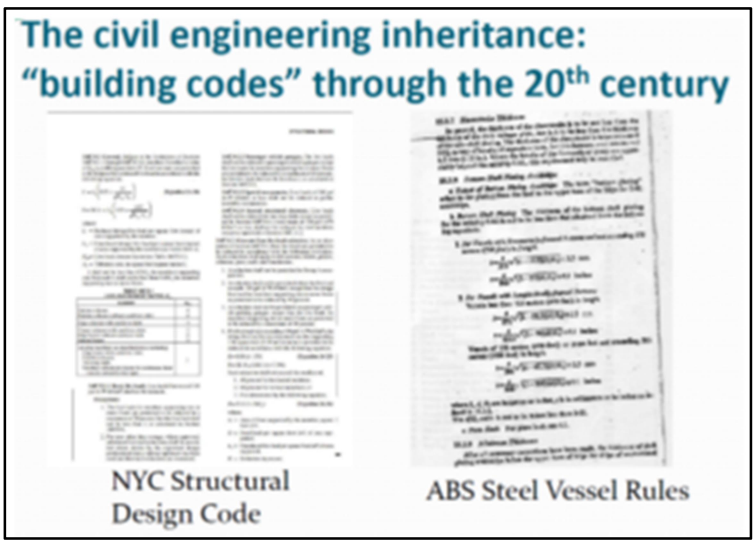

Figure 7. Civil Versus Maritime Building Codes

Aircraft, by contrast, were born in the 20th century, just when physics-based engineering was coming of age. Right from the start, aircraft design was dominated by the likes of German physicist Ludwig Prandtl, who developed advanced theories to explain the aerodynamic performance of lifting surfaces. This was reflected in the amount of research funding poured into aircraft development. In the early 20th century, the U.S. Navy had led the shipbuilding industry in scientific experimentation by funding the construction of two ship model test basins—the Experimental Model Basin (EMB) at the Washington Navy Yard, and another at the University of Michigan. At the same time, almost a dozen wind tunnels sprang up around the nation, including six run by the newly-created National Advisory Committee for Aeronautics (NACA). In the 1902s, the EMB received less than $100,000 annually in appropriations, whereas NACA was being funded to the tune of $1.3 million per year (Ferreiro, 2014).

For some time, in fact, ship classification societies attempted to extend their rules-and-standards methods to aircraft. In 1929, the Aircraft International Register (AIR) was established "to be for commercial aircraft what Lloyd's Register is to shipping" (i.e., intended to provide an internationally accepted set of classification rules for flying machines). For several years, ABS, Lloyd's, and Bureau Veritas established independent aeronautical branches to help the fledgling aircraft industry develop and codify these new procedures and practices. Within a few years, however, national governments took on the role of issuing airworthiness certificates for aircraft, making the role of classification societies redundant. With that, most classification societies shuttered their aeronautical branches, and by 1939, the AIR was disestablished (Ferreiro, 2014).

Conclusions and Recommendations for Further Research

In summary, the reason that development cost for an aircraft is one to two orders of magnitude greater than for ships is primarily due of the extensive use of full-scale prototyping in the aircraft industry for verification and validation. This does not reflect any inherent differences in the two platforms in terms of safety, production numbers, or complexity, but rather it reflects the fact that, even in the 21st century, shipbuilding remains a product of 19th century rule-of-thumb engineering, while aircraft development is the product of 20th century physics-based engineering. Engineering culture, more than the technology itself, is very difficult to change.

Although these cultures are entrenched throughout both industries, it does not mean that change is impossible. Full-scale prototyping, as part of the verification and validation toolkit employed by shipbuilders, can and should be investigated as a through-life-cost benefit (GAO, 2017).

Figure 8. (left) Collision Damage to USS *John S. McCain*, August 2017; (center) Damen Shipyard Full-Scale Test (1998) of Collision-Resistant Ship Structure; (right) Structure Intact After Collision

Such an approach should be looked at in terms of payoff of the initial investment compared with life-cycle improvements to performance and safety. In addition to reducing the teething problems inherent in first-of-class ships, it would also permit the development and validation of systems to protect the vessel and its crew. For example, a recent spate of ship-to-ship collisions, such as the ramming of the destroyer USS *John S. McCain* by a bulbous-bow-fitted tanker in August 2017, has resulted in the loss of lives, property, and combat availability. Such losses might be avoided in future by carrying out full-scale prototyping of collision-resistant systems as were carried out by the Dutch shipyard Damen in 1998 (Figure 8), which demonstrated that a novel structural configuration could absorb the impact of a colliding bulbous-bow tanker with no hull penetration (Ferreiro, 2002).

The U.S. Navy took the lead in scientific experimentation in the early 20th century by funding and constructing model test basins, at a time when the shipbuilding industry was firmly against it. The Navy can once again take the lead by investigating development practices more like those of the aircraft industry, especially in terms of full-scale prototyping of ships to verify and validate the performance of safety-critical systems.

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