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Marine Structural Integrity Programs

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Abstract

This paper summarizes development of advanced Marine Structural Integrity Programs (MSIP) for commercial ships [1]. This procedure was based on the recent developments in Airframe Structural Integrity Programs (ASIP) for commercial and military aircraft. The MSIP procedure suggests a sequence of technical and organizational developments to better ensure the integrity and durability of ship structures during their useful lifetimes. Particular emphasis is given to large crude carriers (tankers). Notwithstanding this focus, it is believed that the MSIP approach is applicable to most commercial ships with few modifications.

Airframe Structural Integrity Programs - ASIP

ASIP for commercial and military airframes are principally the product of the last four decades of very rapid and intense technology and organizational developments [2, 3]. Because of the importance of public transport safety and the very demanding requirements of high performance jet powered aircraft, significant attention has been given to the technological and organizational aspects of airframe reliability.

Formal ASIP developments were initiated in the 1950's with the introduction of jet powered commercial aircraft. In the mid 1970's, there was a major overhaul of ASIP policies for both military and commercial aircraft. This overhaul was in direct reaction to serious structural problems which were encountered in several new airframe structural systems, as well as fatigue cracking and corrosion problems in older in-service aircraft. A critical re-examination was made of the process of aircraft development, procurement, and management. New regulations, design, operation and maintenance guidelines, and certification requirements were developed that are still in force today [4].

A very advanced technology and cooperative organization system for ASIP has been the product of this evolution. Regulatory, manufacturing, and operations - maintenance segments of this industry, and the general public have shared in the costs and benefits of this development. It is important to recognize that ASIP is one of three related and coordinated efforts to achieve serviceability, economy, durability and reliability of aircraft. In development of ASIP, balanced emphasis has been given to the structural, mechanical (avionics), and operational (human, organization) aspects.

In overview, there are two striking aspects of ASIP. The first is how the industry is organized to conduct ASIP. The organizational aspect is highlighted by highly structured and cooperative national and international frameworks for dissemination, archiving and evaluation of information (communications), training, testing, and verifying the capabilities and performance of design, manufacturing, operations, and maintenance personnel [4, 5, 6].

The regulatory responsibilities of ASIP rely heavily on "designees." Designees [6] consist of designated engineering, manufacturing, inspection, and airworthiness representatives who are employees of the airframe manufacturing and owner / operator organizations. Conflicts of interest are minimized by selecting designees that are highly motivated to maintain their reputations for technical integrity and that recognize the stake of the manufacturer and operator in safe operation of the aircraft. Designee functions are conducted under the supervision of the Federal Aviation Agency (FAA) staff and particularly critical activities are performed by FAA staff.

A particularly important function of the organization is the communications and information system operated by the FAA, the aircraft manufacturers, and the owners / operators [3, 4]. A detailed tracking system is established for each aircraft from the time it is proposed for design until the aircraft is decommissioned. The system includes an ASIP master plan, structural design criteria, damage tolerance and durability control plans, selection of materials, processes, and joining methods plans, and design service life and design usage plans.

Weekly reports are issued by the FAA to representatives within each of the three segments of the organization on the problems, results of inspections and repairs, and critical experiences associated with each of the plans. Manufacturers and operators are required to submit daily mechanical reliability reports detailing special manufacturing and operations problems resulting in significant interruptions to these functions.

FAA specialists are assigned to review the reports weekly on given types or classes of aircraft, and as required, issue corrective action directives. These directives are incorporated into the ASIP report system and corrective responses monitored.

The National Aeronautics and Space Administration (NASA) has developed a computer based Aviation Safety Reporting System for the FAA that includes the standard required reliability reports, and in addition, confidential reports on safety problems and violations of procedures within the aviation system. Personnel from any of the three segments of the industry can call in and make confidential reports to the system. The reports are analyzed on a weekly basis to determine if there might be early warning indications of developing airframe durability and safety problems. The reporting system has been operated since 1975 and it has proven to be extremely important in giving early warning indications of developing problems.

The second striking aspect of ASIP is the technical methods and procedures used to assure the integrity of airframes. The technical aspect is highlighted by:

- Intensive and rapid development and application of advanced technologies, firmly founded on past experience, and justified by a combination of analysis, testing, and monitoring (inspection), with emphasis on testing and monitoring founded on sophisticated and realistic analyses.
- A comprehensive approach to engineering for and maintenance of reliability and economy; not only addressing ASIP, but also avionics (mechanical, electrical, equipment systems), aviation systems (airports, airways, air traffic control), and personnel performance integrity programs.
- Design of aircraft structures that not only address functional and strength (capacity) requirements, but also design for damage and defect tolerance; and design for constructability, inspection, and maintainability. Heavy emphasis is given to defect/damage tolerant design and durability design to minimize the risks of low probability high consequence accidents and unanticipated maintenance.

The primary ASIP design objective is [4]:

> "to create an efficient and durable airframe devoid of unanticipated costly maintenance requirements."

This objective is focused in three key technical strategies:

> 1) Damage Tolerant Design - design of an airframe that has the ability to tolerate defects, flaws, and damage, and is able to maintain the critical aspects of capacity and redundancy.
>
> 2) High Quality Production - manufacturing processes and procedures and inspection methods that will assure a high quality airframe.
>
> 3) Excellent Maintenance - painstaking attention to inspection, maintenance, and repair / replacement of critical airframe details throughout life to maintain the critical aspects of capacity and redundancy.

Damage tolerance is the design capability most closely associated with safety. These key ASIP strategies have been based on the experience that the major aircraft accidents that can be traced to structural causes (16 of 216 major accidents from 1958 to 1980 or 7%) have involved the failure of 2 to 3 of these strategies [5].

The ASIP system is not perfect [7]. It is still undergoing intensive development, attempting to make use of current experience and technologies. Due principally to aging problems associated with the commercial fleet, and new more demanding requirements for high performance military aircraft [8], ASIP research and development continues to be intensely conducted throughout the aircraft industry [9, 10]

The result of the present ASIP program is an industry service and safety record that represents a standard of comparison for other industries. United States designed, manufactured, and operated aircraft are in world-wide demand. In spite of its innovative and high technology profile, and public participation, this is an industry remarkably free of dissipating litigation. This is an industry worth examining to determine how MSIP for commercial ships might be improved.

In a historical context, it is important to note that the three components of this industry (operator, manufacturer, regulatory) have grown up together. The organizational and technical development and evolution have been extremely rapid. A hallmark of this development has been a general theme of cooperation and trust among the three segments.

Economic incentives that promote cooperation have been developed and integrated within the three segments of this vital industry. For example, the detail and frequency of inspections can be moderated for owner/operators that have excellent safety records and for manufacturers that have excellent quality assurance records [6, 7]. Owner/operators require that the airframes be durable, increasing in-service time and decreasing repair time. These owners are willing to pay manufacturers more for high quality aircraft. Manufacturers are held responsible for the quality and durability of their aircraft. Their economic incentive is to demonstrate high quality and to sell more aircraft because of the service and durability characteristics.

Components Of Advanced MSIP

MSIP should be one component of a full-scope ship integrity program that addresses:

a) Structural systems (integrity, capacity, durability),

b) Equipment systems (navigation, propulsion, steering, piping, electrical), and

c) Operations systems (vessel traffic control, training, licensing, re-certification).

MSIP should be life-cycle focused. Life-cycle ship structural integrity programs must be initiated at the earliest stages of the design phase, and extend throughout the construction and operations phases.

MSIP should have two fundamental objectives:

1. *Develop a desirable level of structural reliability (integrity, durability) for a newly constructed ship structure, and*
2. *Maintain an acceptable level of structural reliability throughout the ship's life.*

Structural integrity and durability are achieved at a cost. It is desirable to define MSIP that can minimize total (initial and future) costs for given types of ship structural systems, and yet meet minimum safety requirements.

Present experience with MSIP indicates that the principal problem is not the basic capacity of the ship structure; catastrophic compromise of the ship structure is a rare occurrence generally associated with improper operations (e.g. loading - unloading, grounding, collisions) and maintenance (unrepaired corrosion and fractures). Experience indicates that a principal MSIP problem is associated with unanticipated, and in some cases ignored, maintenance of the ship structure. Not only are costs associated with the repairs, but as well substantial costs are associated with down-time and unavailability of the ship for its intended purposes. In some cases, inadequate maintenance has lead to significant internal and external cargo losses. External cargo losses carry with them a heavy financial and political burden of pollution and clean-up. These are costs and burdens to be minimized; in practical terms, they can not be eliminated.

MSIP should address the technical developments that can enable ship owners and operators, builders, and regulators to realize the safety and economic benefits of more durable and reliable ship structures. MSIP technical developments should include:

- *Structural design plans* addressing the life-cycle phases, design criteria, damage tolerance, durability, materials, and operations.
- *Structural analysis guidelines* addressing loadings, strength design, design for durability and damage tolerance, and design for inspectability, constructability and maintenance.
- *Requirements for testing of Critical Structural Details (CSD) and components* to demonstrate capacity, durability, and damage tolerance.
- *Requirements for in-service monitoring* to provide additional information on structure loadings and performance.
- *Development of an industry-wide computer data base system* for archiving design and construction information, operations structural tracking and maintenance tracking including results of monitoring, inspections, maintenance programs, records, repairs, modifications, replacements, and assessments of performance.

A primary goal of MSIP is to help minimize the risks of low probability - high consequence structural failures while maximizing the serviceability and durability of the ship.

Design for Durability

Improvements in MSIP structural analyses refers to development of design guidelines and procedures based on first-principle structure analyses explicitly addressing damage tolerance and durability. This is a next generation of design analyses beyond present classification guidelines and rules. The challenges are in selecting appropriate tools to perform the analyses, and in integrating these tools into ship structures design practice in the form of design guidelines and rules.

The primary objective of design for durability is to create an efficient ship structure devoid of unanticipated costly maintenance and out of service requirements. The extent of design for durability represents a trade-off between initial costs and long-term operating costs. The objective is to make a sufficient initial investment in durability quality to forestall escalation in future maintenance and out-of-service costs.

Experience indicates that fatigue problems develop because of ignored or inaccurately characterized loadings, poorly designed connections (e.g. inappropriate or no analyses, high stress concentrations, bad load transfer mechanisms), poorly constructed systems, poorly maintained systems (e.g. corrosion allowed to initiate or exacerbate fatigue) [11]. Loading and load effects uncertainties generally dominate fatigue analysis uncertainties.

Connections with low stress concentration factors, accurate determination of sustained and cyclic straining histories, use of ductile and fatigue resistant materials (including weldments), robust (damage tolerant) system designs, construction and maintenance quality assurance and control, and perceptive design methods are the key defenses against fatigue damage or low durability structure systems.

Fatigue analyses consist of characterization of short and long term cyclic conditions (loading-unloading, hydrostatic, hydrodynamic, aerodynamic, machinery, equipment), determination of the cyclic forces and strains in the elements that comprise the system, determination of the potential degradation in strength and stiffness of the elements that comprise the system, and evaluation of the acceptability of the fatigue design and associated MSIP. The marine industry has developed sophisticated analytical techniques to allow the industry to realize the goal of explicit design for fatigue durability. The challenge is to reduce these techniques to practical engineering guidelines and to realize the fatigue design premises in construction and maintenance. Additional development of CSD configurations to minimize fatigue durability problems and facilitate construction, inspection, and maintenance are needed [12].

In the drive for weight savings and the associated initial cost savings, many ship structure designs have employed High Tensile Steel (HTS) details and components. Test results and experience indicate that it is only in the high stress - low cycle region of fatigue straining where HTS has a higher fatigue strength; this region does not contribute much to the total damage. Unless the elements have been dramatically under-designed for normal operations and extreme conditions and are subject to very high stresses during normal operations [13], it is the high-cycle, low-stress region that contributes the majority of fatigue damage. HTS strength (parent material and weldment) is achieved with a cost to fatigue resistance and ductility. As pointed out by recent experience, much more care has to be taken in the design and construction of structural details to minimize stress concentrations when using HTS [14]. Proper attention must be given to the notch toughness and fracture arresting properties of the steel and weldments.

Related Considerations

Design for durability includes not only assessment of the effects of repeated loadings as previously discussed, but as well the associated aspects of design for constructability, corrosion protection, inspectability, and reparability [1]. Design for constructability is intended to help assure that the ship structure system that is designed can be effectively (high likelihood of reaching quality objectives) and efficiently (lowest reasonable cost) constructed. This requires that the design and construction procedures and plans be thoroughly and properly integrated.

Design for inspectability is intended to help assure that the ship structure system can be adequately inspected and surveyed, during the construction phase and during the operations - maintenance phase [15]. Inspections are intended to disclose defects and damage. The reliability of inspectability is directly connected with the design for fatigue. Given that the degree of inspectability of the structural system is low, either during construction or operations - maintenance, then the requirements for defect tolerance (robustness) in the system are increased. If the degree of inspectability is high and defects and damage can be detected at early stages, then repairs can be made before the strength of the system is degraded significantly. Robustness requirements then can be decreased.

It is here that important questions should be raised concerning how ship structures are presently designed. Designs are focused on creation of minimum weight systems. These emphasize the use of thin plates (to contain cargo and ballast, and exclude sea water) reinforced by a multitude of frames and stiffeners (to provide stiffness and strength). Consideration of design for highly automated fabrication provides important additional constraints on the structural configurations and assemblages.

Primary attention needs to be directed to recognition of the very limited degrees of inspectability of the structural system, rather than assuming that inspections can or will be done with a high degree of detection and accuracy. This would tend to constrain the design of the system to use of thicker plates and fewer frames and stiffeners and design for durability without depending on inspections to assure adequate durability. Design for inspectability should also address provisions to facilitate human access and inspections. Adoption of greater spacing for members to facilitate access, avoiding blind spots in the structural arrangements, and providing access facilities (openings, ladders, walkways, removable staging systems) for entering important parts of the structure. Cleaning, degassing, and lighting systems also need to be provided. In addition, design for inspectability should address development of and provisions for remotely operated inspection systems and instrumentation systems [15].

Design for repairability should include explicit consideration of how the system can be repaired when there is damage or defects or when the system must be maintained [16]. Too often, in the relative comfort of the design office, it is assumed that the critical structural details can be easily accessed, damaged or defective elements removed, and repairs made. Planning must be done at the design stage on how repairs and maintenance will be done. Again, this requires proper and thorough integration of the repair yard and maintenance objectives and capabilities with the other design objectives.

Corrosion Durability

A key element in design for durability is corrosion protection, particularly for the critical internal structural elements associated with cargo and ballast tanks of crude carriers. Experience indicates that the most severe corrosion rates can be expected in ballast tanks [17]. The corrosion effects may be the worst when the ballast tanks are empty or partially full. In this phase, cathodic protection can not protect the metal not covered by water. Cathodic protection efficiency can be reduced by sediment cover in the bottoms of the tanks. Corrosion can be exacerbated by adjacent heated cargo tanks.

Corrosion is also a problem in the cargo tanks [18]. If these tanks are coated, they experience more of the pitting type of corrosion rather than general wastage. If not coated, general corrosion can be severe in tank bottoms and on stringer platforms. Tank washing and the area under loading line outlets can act to remove coatings and the protection provided by waxy crude cargoes. Breakdown of coatings in the under-deck area of cargo tanks can be very severe. Coating breakdowns and partially coated areas can act to accelerate local corrosion.

Coatings and cathodic protection are practical protective measures [19]. Design that eliminates or minimizes traps for water and sediment, and provides scour or erosion protection must be encouraged. Coatings must be properly designed to match the projected expected service and maintenance, and flexibility of the components to be protected. They must be properly applied, cured, and maintained. Similar statements regard the design, installation, and maintenance of cathodic protection systems.

Improvements are needed in coatings and cathodic protection systems, and design of compatible structural - coating systems. The major problems are showing up in improperly designed, applied, and maintained corrosion systems, and incompatibilities between structural and corrosion protection systems (e.g. flexible bulkheads covered with stiff coatings, corrosion cells set up between the parent material and the weld heat-affected zone resulting in "grooving" corrosion). There are some important construction equipment and applications advancements that need to be realized in new build and repair yards before improved coating systems can become a reality.

Robustness

Developments in design for damage and defect tolerance include explicit requirements and procedures for design of critical structural details and systems for:

a) existence of initial primary damage (crack size) based on specified materials and construction quality control procedures,

b) existence of continuing damage (crack growth) based on the design loadings, maintenance interval, and in-service inspection quality,

c) load path failure or crack arrest, and

d) acceptable residual strength [20].

Experience indicates that there is a high likelihood that the hull structure will suffer damage from collisions, groundings, loading and unloading operations, and explosions and/or fires. Particularly as these hazards can compromise the ability of the hull structure to prevent escape of hydrocarbon cargoes, attention should be given to the structural configuration and design aspects to minimize such escape. It will be very important to consider such sources of damage in design of new configurations of tankers.

The critical structural details and systems for durability and damage tolerance evaluations should be those which contribute significantly to carrying environmental and operational loadings, and whose failure, if undetected, could lead to loss of the ship or its cargo. Most important in this system is the identification of acceptable or tolerable defects in critical structural elements. This provides an important basis for designing inspection programs and determining when repairs and renewals must be made [13, 21].

It is critical that the system for identifying the acceptable or tolerable defects recognize the extent of robustness in the ship structure system. Structural robustness is the integrated effect of:

a) redundancy (alternative load paths),

b) ductility (ability of the element, component, and system to maintain load resistance with repeated plastic or nonlinear straining), and

c) excess capacity (ability of elements within the system to fail and transfer their loadings to other elements).

It is important to realize that in the past, design for damage and defect tolerance has been implicit in many ship structure design processes. In many cases, this experience based, implicit approach has developed ships with acceptable serviceability and capacity characteristics. Given new ship structural systems, such as some proposed double-hull VLCC's and ULCC's, careful consideration must be given to the related requirements for structural system robustness and durability. Explicit analyses should be conducted to assure that adequate degrees of robustness and durability are present.

Considerations of both durability and robustness raise the question of where in the structure system these considerations should be focused. This question can be addressed by evaluating the following factors concerning each of the structural elements that comprise a structural component, and the structural components that comprise the structural system: a) consequences of damage or defects, b) likelihood of damage or defects, and c) extent of damage or defects affecting multiple structural elements.

If the damage, defects, or absence of a structure element or component leads to a significant compromise of structural integrity (capacity, containment, stability), then these elements or components can be classed as primary critical structure. If they do not, then they can be classed as secondary non-critical structure. If the likelihood of damage or defects of the primary critical structure elements and components are high, then the requirements for durability and damage tolerance are high. If not, then the requirements for durability and damage tolerance are lower.

Given the expected damage or defects, if the extent of defects and damage (e.g. number of elements and components involved, reductions in capacity and ductility) is extensive, then the requirements for durability and robustness are high. If not, then the requirements for durability and damage tolerance are lower.

It is here that inspectability and repairability of the system are important considerations. If inspections and repairs can be relied upon to limit the likelihood of damage or defects and the extent of damage or defects, then requirements for durability and robustness can be relaxed. If not, then they must be increased to be consistent with the expected or planned degrees of inspectability and repairability.

Inspections and Monitoring

A key consideration in adaptation of the technology of ASIP to MSIP regards inspections and inspectability of the two systems (air frames and ship structures). Inspections and monitoring are taken to include the gathering of information and data on: a) design (testing, verification), b) construction (materials, fabrication, sea trials), c) operations (loading - unloading, voyage), d) maintenance (disclose damage, assess repairs), and e) casualties.

Air frames can be subjected to intensive inspections during their design and production and extensively flight tested to assure the serviceability and capacity of the air frame. While in service, they can be brought into a hangar and subjected to intensive visual and non-destructive testing. Excessively damaged or defective components can be readily replaced.

This is in dramatic contrast with a modern VLCC or ULCC. Such a ship can involve 100 to 200 acres of structural steel surface, and 1,000 to 2,000 miles of welding. In contrast with the relatively benign atmospheric environment, these ship structures are operated in an extremely hostile environment of salt water, storm waves, and cargoes of liquid - gas hydrocarbons. To subject all of the steel and welding in a VLCC or ULCC to intensive visual and non-destructive testing during construction would not be practical; time and costs would be prohibitive. Sea trials rarely are of a duration or intensity severe enough to disclose critical design or construction flaws.

During construction, the first line of inspections for quality assurance and control is training and qualification of the construction personnel [22]. The second line is the provision of positive incentives and resources (adequate working conditions and equipment) for high quality workmanship. The third and last line is the use of inspectors and spot-checking with non-destructive testing.

During maintenance operations, detailed inspections are even less practical compared with inspections during construction [23]. Access and lighting are extremely limited in performing inspections of critical internal structural details. Due to darkness, water, dirt (sediment in bottom of ballast tanks and coating structure elements), and residual accumulations of hydrocarbons, inspections are hazardous. Aided and unaided visual techniques are the primary inspection technique.

Gauging surveys are difficult to perform because of the problems associated with obtaining accurate thickness measurements, accurately determining the locations of the measurements, recording the measurements, and evaluating the data [15, 17]. Corrosion pitting surveys are similarly difficult and involve a high degree of subjectivity.

Inspector experience and training vary widely; thus, the quality of inspections also vary widely.

Marine accident reporting and investigating systems have been implemented, but need continued development. Accident investigators need to be qualified and properly trained. These investigators must be given a procedural system that will guide their investigations, and a data recording system that will permit the results to be efficiently archived and retrieved for analysis and evaluations. This is particularly important when it is recognized that about 80 % of major ship casualties or difficulties are due to human and organization errors [24]. *The accident reporting and investigating system needs to be configured to properly address the human and organization elements.*

While improvements in ship design and inspection methods and equipment are possible and should be encouraged, it does not appear to be reasonable to expect that ASIP inspection methods and reliability can be simply extrapolated to MSIP. At the present time and in the near future, current ship inspection methods and programs should be relied on only to disclose very major or obvious defects and damage to critical structural elements. Practical limitations on inspections and inspectability of ships places important and significant constraints on the other portions of MSIP.

Similarly, the use of instrumentation and performance monitoring systems are more severely restricted in the ship environment [25]. Instrumentation transducers and leads have very limited durability in this environment. While improvements in instrumentation and monitoring equipment and systems are certainly possible and should be encouraged, practical limitations on present instrumentation and monitoring of ships places important and significant constraints on other portions of advanced MSIP.

The major implications for MSIP concerns the basic design of the critical structural elements. The ship structure system must be designed so as not to rely on accurate inspections. Inspections should be one means of helping assure a given level of minimum quality, durability, and strength in the structural system primarily by disclosing unexpected flaws in the system. This places a heavy burden on the design, construction, and maintenance of the structural system; it must be designed, constructed, and maintained to be durable and robust (damage and defect tolerant), fundamentally independent of reliance on highly accurate inspections and monitoring. Steel, and high quality design and construction are used in lieu of more sophisticated high quality inspection based maintenance procedures. Future developments in inspection systems may allow use of more economic durability, robustness, and maintenance approaches.

Structural Monitoring and Tracking

Improvements in MSIP structural monitoring refers to intensified deployment of instrumentation and monitoring systems to determine loadings, response, and performance characteristics of critical structural elements while the ship is in service. Additional development efforts need to be focused on development of practical and robust ship structure instrumentation systems [25].

Uncertainties in loadings (environmental, operating) constitute one of the largest sources of uncertainties in ship structural reliability and durability. A primary objective of instrumentation systems is to help reduce loading uncertainties. Instrumentation systems can provide data to validate structural response and performance analysis models. Because of the dramatic influences of crew operations on both ship loadings and ship structure performance, monitoring systems also can provide important information to indicate when operating envelopes are being exceeded.

Large uncertainties in loadings and performance result in the need for large factors of safety to achieve a given level of reliability and durability. Uncertainty costs. Experience with a variety of marine structures indicates that the knowledge that can be gained from well conceived instrumentation and in-service monitoring programs can result in significant cost reductions; *ignorance costs.*

Improvements in MSIP maintenance tracking refers to development and implementation of life-cycle, full scope, industry sector wide integrated computer based systems for archiving, analyzing, and tracking ship structure performance characteristics [26]. These systems are intended to provide a long-term corporate memory to reflect on the adequacy of design, construction, and maintenance practices, and to alert the responsible parties to important symptoms of ship structure problems [27].

Structural Durability and Economy

As noted earlier, a fundamental objective of MSIP is to establish and develop a desirable level of structural reliability (integrity and durability) in new ships, and then to maintain that reliability at acceptable levels. This objective is subject to two important inter-related and complementary constraints. The first constraint can be identified as the required or desired "standards of performance" for the newly constructed ship structure and for operations and maintenance of the ship structure during its life. These standards can be expressed in qualitative and quantitative terms.

The second constraint can be identified as a search for the ship structure system and MSIP that can result in minimum expected life cycle costs associated with that structure [28 ,29]. This search can be expressed alternatively as a search for the ship structure system that will have the highest life-cycle utility. This is essentially a problem in balancing quality and reliability with initial and future costs.

Initial costs include all of the costs associated with the design, construction, and commissioning of the ship structure. Future costs include all of those costs associated with operations, maintenance, and loss of serviceability. Loss of serviceability costs can range from those associated with down-time and loss of income due to the down-time to catastrophic loss of serviceability costs associated with complete loss of the ship and cargo. Higher reliability (capacity - durability - robustness) structure systems should be expected to have higher initial costs. Conversely, they should be expected to have lower future costs due to less maintenance and loss of serviceability costs. The search for desirable durability in the ship structure should be focused on defining the ship structure system and MSIP that can result in the minimum total costs [1].

Organizational Developments

Advanced MSIP must address the organizational developments that can lead to more effective and efficient life-cycle and full-scope ship integrity programs. These issues address how the organizational sectors of the industry can work more effectively toward a common set of advanced MSIP goals. Technical "fixes" alone will not result in the desired objectives of an advanced MSIP.

There are four principal organizational sectors involved in this development:

a) regulatory agencies,

b) Classification Societies,

c) manufacturers, designers, builders, and repairers, and

d) owners and operators (Fig. 1))

In the case of ASIP, the Federal Aviation Agency, the U.S. aircraft manufacturers, and the U. S. operators exert dominant and controlling influences on the world wide industry of commercial air transport. This is a very different situation than for the U. S. based crude carrier industry. In this case, the world wide organization is much more diffuse; it is based outside the U. S. The organizational developments required to realize an advanced MSIP are much more difficult to achieve.

The U. S. based ship industry can help take the lead in a world-wide effort to institute advanced MSIP based on the premise of improving the life-cycle economics of the transport of crude oil and refined products. Efforts by owners and operators (e.g. Tanker Structure Co-operative Forum, TSCF), Classification Societies (International Association of Classification Societies, IACS), and regulatory bodies (International Maritime Organization, IMO) have been initiated in this direction.

Insurers and P&I Clubs also can play an important role in advanced MSIP developments. When ship structure durability problems advance to the point where there are serious concerns for the life, cargo, and property aspects of the ship, then insurance and insurance premiums are an important consideration. Insurance organizations are businesses that must compete for a share of the market. Premiums must be kept low to encourage business, but not so low as to encourage bankruptcy of the business in the case of unexpected large losses. It would seem prudent for insurance companies to develop insurance premium structures that could provide positive incentives for development and realization of advanced MSIP.

One of the primary organization implications of advanced MSIP regards the continuation of the industry's heritage of individual custom designed ships. Given the increased demands of design, testing, and construction to achieve durable CSD and ship framing systems (and the costs and time associated with this activity), such custom designs would not seem to be in the industry's best interests. Advanced MSIP would implicate the development of fewer basic classes of ship structural systems.

Goals and Responsibilities

Of particular importance in MSIP developments is agreement between the principal sectors of the goals and responsibilities of each sector. Based on comparable ASIP organizational developments, MSIP responsibilities for each of the four segments is suggested as follows:

1. *Regulatory - responsible for definition and verification of compliance with goals and policies of MSIP.*
2. *Classification - responsible for development of classification rules that will guide and verify design, construction, and operation of durable and reliable ship structures that meet regulatory requirements.*
3. *Manufacture - responsible for designing and producing a vessel with appropriate seaworthiness, structural integrity, and durability.*
4. *Operations - responsible for design and maintenance of ships and the safe and economic operation of the vessels.*

The MSIP organizational developments should promote intensely communicative cooperative and supportive interactions among the major segments of this industry. The organizational developments must be based on continuous proactive structural integrity management that involves control or verification of adequacy of the process and of the performance of the process. The organizational developments must promote a disciplined and structured approach to MSIP.

MSIP organizational developments should result in the ship structure achieving a degree of reliability and durability that is acceptable to the sectors responsible for ship operations. Reliability and durability are achieved at a cost. Reliability and durability should be in balance with the risks or hazards associated with the particular type of ship operations. Risks reflect the likelihood of accidents and the potential consequences of those accidents. Higher risk operations imply the need for higher levels of reliability. Durability problems can be reflected in both unanticipated maintenance costs and degradation in the capacity of the ship structure.

Profitability from the ship operations must provide the financial resources required to achieve the degree of reliability and durability that is deemed desirable or acceptable. All of these organizational measures to improve MSIP cost money, time, and effort. Positive incentives must be created for owners / operators to adopt and require advanced MSIP. The consumer and general public must be willing to pay for the improvements required to increase the reliability and safety of this segment of commercial transportation. The regulatory, owner - operator, classification, and producer segments of this industry must agree on the extent of development of MSIP appropriate to assure the reliability and durability of a particular class of ship operations.

Conclusions

The commercial ship industry has the basic technology required to realize advanced MSIP. Additional work is needed to organize this technology so that it can be effectively and efficiently applied by the ship designer, constructor, and operator. Technical improvements in design for fatigue, corrosion protection, and inspections and monitoring systems are needed and these are within the present reach of the industry.

The major impediments to realization of advanced MSIP are founded in the organization of the industry and its financial philosophy. If advanced MSIP is to become a reality, positive incentives and "high reliability" organizations must be developed to encourage the industry to embrace the organizational and technical tenants of MSIP.

It is reasonable to expect that advanced MSIP will result in increases in initial costs. These increases must be outweighed by the reductions in future costs associated with maintenance, loss of service, and other unanticipated costs associated with durability of the ship structure. This requires a long-term view, recognition of potential future costs, and an understanding of the true contributions to company and country profitability developed by commercial shipping. Organizational quality, performance, and integrity in ship operations, regulatory, classification, building - repair sectors must change to allow realization of the goals and objectives of advanced MSIP.

> "Nothing worthwhile is quick, easy, or free."

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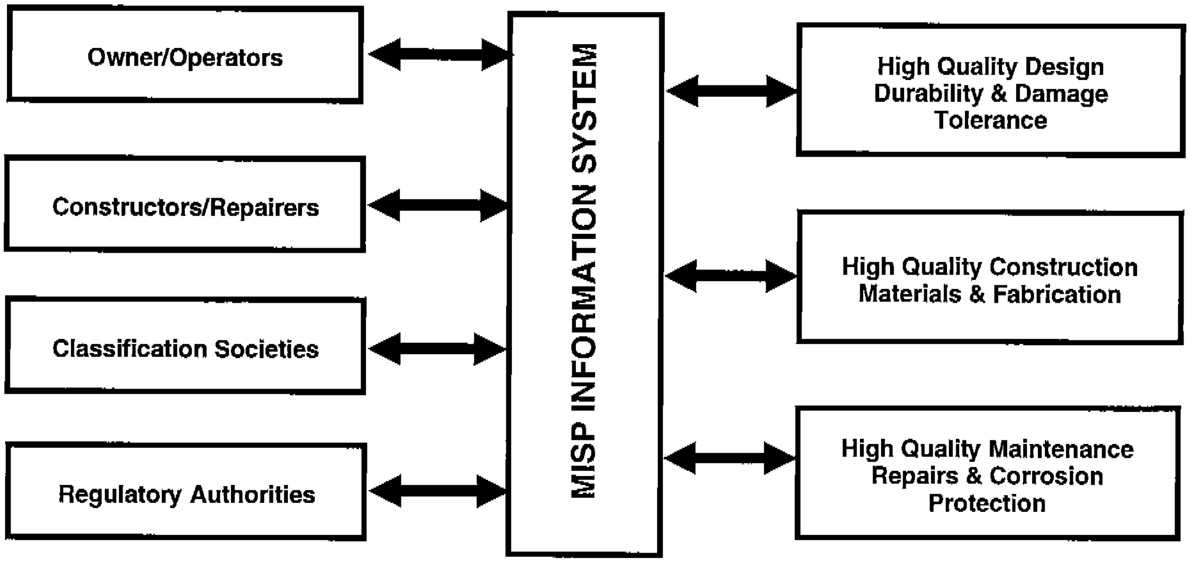

Figure 1
Principal Components of Advanced MSIP