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The Evolution of Inspection and Repair Procedures for Ship Structures

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ABSTRACT

The aim of the paper is to discuss the problem of inspections of ship structures.

Ships have quite a long tradition as regards dealing with problems connected with steel weldings and their design philosophy is rather particular. It can be summarized as follows:

- ships are considered damage tolerant structures and the problem of propagation of fatigue cracks is not directly checked in the design;
- material, fabrication and design requirements are foreseen in order to reduce the risk of brittle fracture and fatigue collapse;
- non destructive tests and periodic surveys are foreseen during construction and the operating life, in order to detect possible damage.

Within this philosophy, over the past decades, there has been an evolution in terms of material, fabrication and design standards as well as inspection procedures largely validated on the basis of past experience. The question is whether these procedures are optimized with respect to safety and costs or whether there is a need for more rational approaches to the problem.

It appears in fact that, for traditional large sized ships, very detailed inspections are not economically feasible; on the other hand, in the case of either novel concepts or new fabrication procedures, experience is lacking and more rational approaches should be applied.

A different approach to the inspection and maintenance problems is adopted in the offshore field, where the modern tendency is to try to optimize both initial design requirements and the planning of inspections and repair by means of reliability based approaches.

The perspectives of extending the criteria and methodologies developed in the offshore field to ships are envisaged in this paper and a brief outline of the relevant problems is given.

1. HISTORY OF SHIP INSPECTION

Ships and shipping as a means of carrying goods and people are very old concepts; ships were very definitely invented before naval architecture and design, and they evolved, until some decades ago, through empirical design. The safety and risk prevention policies were based more on heuristics and experience than on rational thinking, the latter being impossible due to a total lack of theoretical knowledge.

The same approach having been followed for fabrication technology and ship management, naval architecture and shipbuilding of the past may be seen as an "ARS", in the Latin meaning, which has been able to produce a substantial evolution of ships by successfully adopting a "trial and error" optimization procedure.

As often happens in technological progress, the evolution is not a smooth, continuous process but is characterized by crises and jumps.

Three crises-jump moments stand out in the story of naval architecture: WOOD to STEEL, RIVET to WELD and MEDIUM to LARGE which represented an evolution in the existing construction and in-service inspections criteria and procedures.

The introduction of steel has brought into ship structures the consequences of fatigue and corrosion which lead to a faster deterioration of the structural integrity with respect to the wooden ship. A tentative approach was to resort to some structural redundancy using substantial extra thickness to compensate for corrosion.

As far as the design is concerned, the solution was found by applying some "trial and error" procedures. Conversely, the use, developed in the wooden ship, of inspecting the vessel after any large storm only, evolved into inspections periodically scheduled.

Perhaps, more dramatic for the shipping industry was the passage RIVET to WELD due to problems like brittle fracture and fatigue: in particular, the consequences of the first, which can be dramatic, made the passage slower than in other areas of engineering. In fact, on the one hand, when the RIVET disappeared, so did an implicit and effective crack arresting device, and as a result there was a need for a substantial improvement in the steel properties which meant considerable effort by the steelmaking industry. On the other hand, the extensive use of welding increased the presence of stress concentration spots which are typical of welded details; if these are not drastically reduced by appropriate design and fabrication methods, which also required a lot of effort by designers and shipyards, they might not only be potential triggers of brittle fracture but also an initiation of fatigue cracks.

Thanks to a continuous improvement in steel properties and performance as regards weldability and notch toughness, in welding consumables, with related properties and soundness of the deposited metal, and in the design of structural details, the occurrence of brittle fracture steadily declined from the peak period in the 40's.

Fatigue and corrosion have become serviceability (strength deterioration) rather than survivability problems which have to be, and generally are, detected and rectified in due time, i.e. before they can begin to affect the vessel's safety by leading to local and eventually overall collapse.

The fairly successful way followed, could be seen as an attempt made toward a FAIL SAFE design philosophy with the scope of providing the structure with an adequate safe life period, which may be stated as follows:

1. a crack-free period, or one during which the growth rate of cracks is sufficiently low so as not to escape timely detection within the given life period, must be guaranteed;

2. the capability of carrying a predetermined load under a given amount of damage before it can be detected, must exist;

3. inspections which satisfy points 1 and 2 above must be possible, during the life period, so as to allow damaged elements to be repaired in time.

It is clear that a similar approach can be applied only to those areas which are inspectable. It is thus mandatory that blind or uninspectable areas be kept restricted to those which do not influence the safe behavior of the whole structure; this condition was easily satisfied when the ship's dimensions were modest and the holds and other important spaces could be inspected well.

What made the interested parties and experts begin to lose confidence in this philosophy when applied to ships, was the MEDIUM to LARGE crisis i.e. the evolution, in the last 20-30 years, toward very large or very specialized ships for which both the dimensions and/or the structural solutions make it quite difficult if not impossible to perform an adequate global inspection, inspections which, in any case, become very expensive and time consuming (i.e impractical).

The remedy was to try to increase the severity of application of the damage tolerance + periodic inspection philosophy by improving it. Therefore, the most practical ways were and are to go towards the adoption of structural details specifically designed to reduce stress concentration and to reduce the corrosion rate by means of either coating or cathodic protection. That means essentially being able to intervene during the design and construction stages so that some random on-spot inspections are sufficient to evaluate the state of health of the whole vessel.

Class Society requirements, in fact, include periodical ("Special") detailed surveys to be carried out every 4/5 years, the level of severity increasing as the ship's age increases (see Tabs.1÷3). Special surveys are supplemented by annual bottom/docking surveys aimed at checking the ship's status. If damage or other defects occur in the course of ship operations, which the owner is expected to report to the Class Society, additional occasional surveys are usually performed.

2. PRESENT STATUS AND GOALS

Out of the 12045 serious casualties which occurred during the period 1979-86, to ships above 100 grt, 1019 (8.5%) were due to hull damage [1] i.e. an average hull damage frequency of 2.55 per 1000 ship years.

Moreover, while very few isolated events occurred due to overall failure of hull girder strength, the cause of damage is corrosion for almost all

Age ≤ 5 Special Survey No. 1	5 < Age ≤ 10 Special Survey No. 2	10 < Age ≤ 15 Special Survey No. 3	15 < Age ≤ 20 Special Survey No. 4
1. Overall Survey of all tanks and spaces 2. Close-up Survey: a) One complete transverse web frame ring including adjacent structural members (in one ballast tank, if any, or a cargo tank used primarily for water ballast) b) One deck transverse including adjacent deck structural members in one cargo wing tank c) Lower part of the girder system including adjacent structural members on one transverse bulkhead in one ballast tank, one cargo wing tank and one cargo centre tank	1. Overall Survey of all tanks and spaces 2. Close-up Survey: a) All complete transverse web frame rings including adjacent structural members in one wing tank (in one ballast tank, if any, or a cargo tank used primarily for water ballast) b) One deck transverse including adjacent deck structural members in each of the remaining ballast tanks, if any c) One deck transverse including adjacent deck structure in one cargo wing tank and two cargo centre tanks d) The complete girder system including adjacent structural members on the transverse bulkheads in one wing tank (in one ballast tank, if any, or a cargo tank used primarily for water ballast) e) Lower part of the girder system including adjacent structural members on one transverse bulkhead in each of the remaining ballast tanks, one cargo wing tank and two cargo centre tanks	1. Overall Survey of all tanks and spaces 2 Close-up Survey: a) All complete transverse web frame rings including adjacent structural members in all ballast tanks and in one cargo wing tank b) One complete transverse web frame ring including adjacent structural members in each remaining cargo wing tanks and one bottom and one deck transverse in each cargo centre tank c) The complete girder system including adjacent structural members on the transverse bulkheads in all cargo and ballast tanks	1. Overall Survey of all tanks and spaces 2 Close-up Survey as for Special Survey No. 3 with additional transverses as deemed necessary by the Surveyor

Table 1 - Minimum requirements to overall and close-up surveys (taken from [1])

Age ≤ 5 Special Survey No. 1	5 < Age ≤ 10 Special Survey No. 2	10 < Age ≤ 15 Special Survey No 3	15 < Age ≤ 20 Special Survey No. 4
1. Cargo tank boundaries facing ballast tanks, void spaces, pipe tunnels, fuel oil tanks, pump rooms or cofferdams	1. Cargo tank boundaries facing ballast tanks, void spaces, pipe tunnels, fuel oil tanks, pump rooms or cofferdams 2. All cargo tank bulkheads which form the boundaries of segregated cargoes	1. Cargo tank boundaries facing ballast tanks, void spaces, pipe tunnels, fuel oil tanks, pump rooms or cofferdams 2. All remaining cargo tank bulkheads	1. Cargo tank boundaries facing ballast tanks, void spaces, pipe tunnels, fuel oil tanks, pump rooms or cofferdams 2. All remaining cargo tank bulkheads

Table 2 - Minimum requirements to tank testing (taken from [1])

Age ≤ 5 Special Survey No. 1	5 < Age ≤ 10 Special Survey No. 2	10 < Age ≤ 15 Special Survey No 3	15 < Age ≤ 20 Special Survey No. 4
1. One section of deck plating for the full beam of the ship within 0,5 L amidships (in way of a ballast tank, if any, or a cargo tank used primarily for water ballast) 2. Sufficient measurements of structural members subject to Close-up Survey for general assessment and recording of corrosion pattern 3. Suspect areas	1. Within 0,5 L amidships: a) Each deck plate b) One transverse section 2. Sufficient measurements of the different structural members subject to Close-up Survey for general assessment and recording of corrosion pattern 3 Suspect areas 4. Selected wind and water strakes outside 0,5 L amidships	1. Within 0,5 L amidships. a) Each deck plate b) Two transverse sections 2. Sufficient measurements of the different structural members subject to Close-up Survey for general assessment and recording of corrosion pattern 3. Suspect Areas 4. Selected wind and water strakes outside 0,5 L amidships	1. Within 0,5 L amidships: a) Each deck plate b) Three transverse sections c) Each bottom plate 2. Sufficient measurements of the different structural members subject to Close-up Survey for general assessment and recording of corrosion pattern 3. Suspect areas 4. Selected wind and water strakes outside 0,5 L amidships

Table 3 - Minimum requirements to thickness measurements (taken from [1])

kinds of ships and, in particular for oil tankers, fatigue (see Fig. 1 [2]).

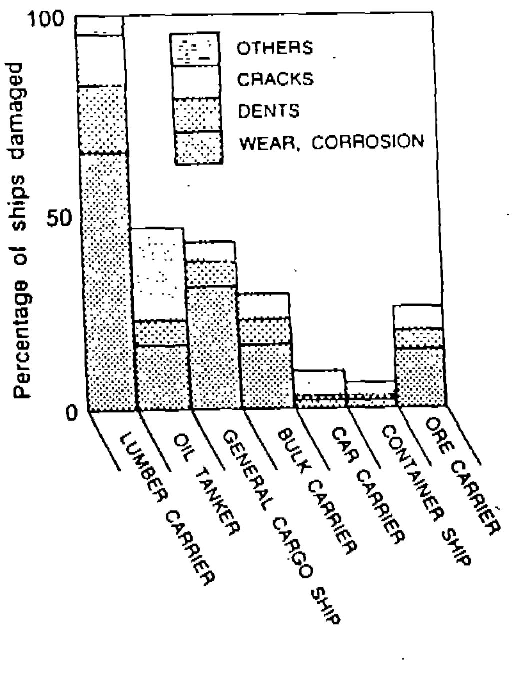

Fig. 1 - Structural damages to ships in 1976-84 (excl. casualties) (taken from [2])

The above figures support the conclusion that quite an acceptable equilibrium has been achieved between a relatively high structural redundancy and the extent and method of on-spot periodic inspections.

But now, if one looks at the last few years, it can be seen that the present trend of demand, which might involve making a new jump, is toward:

- a minimization of structural weight and thickness (in the two periods from 1953 to 1965 and from 1965 to 1985 steel weight reduction was about 25% and 15% respectively, according to [3]) which might be achieved by:
- an extensive use of HTS
- increased specialization of ships
- a possible reduction in fabrication cost (e.g. by an increase in automation procedures in shipbuilding)
- optimized lifetime economy
- a reduction in incidental maintenance versus an increase in planned maintenance
- improved flexibility.

It is clear that any attempt to comply with such a demand without upgrading the extent of the Fail Safe philosophy as applied until now will upset the above-mentioned equilibrium and lead either to significantly greater hull damage and/or a shorter service life than expected.

Leaving aside both the true approach, not practically applicable to ship structures, and Maintenance Free structures, which would require large initial investment and a substantial increase in structural weight, perhaps a solution might be found by looking for higher technology, that is to say an "Enhanced Fail Safe" design philosophy like the one developed in the offshore industry, based on:

- either deterministic or stochastic fatigue design associated with fatigue target safety margins chosen according to the inspectability and structural importance of the detail under consideration;
- a good compromise between degree of reliability and fabrication cost of details;
- high standard of Q.A. and Q.C. procedures adopted in fabrication;
- application and maintenance in service of coatings and cathodic protection to reduce corrosion, suitably diversified depending on the areas to be protected;
- selection of critical details to be inspected both on the basis of experience and of theoretical evaluations;
- IRM (inspection, repair and maintenance) procedures based on an optimum scheduling;
- monitoring of the structure to assist both operation and maintenance duties;
- development of data bases for typical damage occurrences and inspection results.

If and when the goal is reached, a ship design performed in line with the enhanced Fail Safe criterion will rationally weigh fabrication, maintenance and operational aspects on a cost effective basis.

As far as the inspection activity is concerned, a clear identification of possible critical details during the early design stages will be of considerable help to the surveys of the individual ship in addition to the surveyors'experience. A Planned Maintenance System for the hull structure may also be agreed with the Classification Society, to be updated on the basis of the results of the inspections.

3. PROBLEMS

What are the problems which have to be faced when undertaking to follow an enhanced Fail Safe criterion? In Tab. 4, a sample of the main problems is given, subdivided by topic (R=research, D=design, F=fabrication and O=operation) and by expected solution time (1=short, 2=medium and 3=long term).

PROBLEM	CLASS	TIME
uncertainty in fatigue data	R	3
crack growth rate in salt water	R	3
local fatigue design (particular relevance to HTS structures)	D	1
corrosion fighting systems (particular relevance to HTS structures)	F/O	1
annulment of thickness HTS gain by fatigue	R	3
blind areas	D	1
built in arrangements for access to structures	D/F	1
QA and QC in yards (including automated yards)	F/O	2
human error to be taken into account	D/O	2
specialization of vessel to reduce unrestricted navigation (design operational profile)	D	3
reliability of NDE	R/F/O	2
underwater inspections (including ROV)	R/O	2
operation response monitoring to help the navigator the feel the vessel's motions (and response)	O	1

Tab. 4

It is encouraging to see that research is already moving toward a solution to many of the above problems and results have been obtained e.g. in areas such as: fatigue design of structural details [4,5], corrosion-fatigue [6], reliability based fatigue [7,8,9,10], life expectancy assessment [11,12], reliability based optimization of inspection schedule and cost [13, 14,15], probability of detecting cracks by inspections [16,17,18,19] and use of expert systems for residual life estimate [20].

Other initiatives worthy of mention are those of the ISSC [2], aimed at providing service experience as a background to theoretical investigations, the Tanker Structural Cooperative Forum [21], which has given guidance on survey preparation and execution as well as a catalog of structural detail failures and repair, IACS [22], which deals with matters like the inspection of ballast tanks with particular regard to corrosion detection and SSC which has produced excellent studies dealing with ship inspections and structural details [2,4,5].

4. (TENTATIVE) CONCLUSIONS

After the drop experienced in the 80's, the demand for tonnage is now increasing (see Figs. 2 and 3); in particular, about 45 million tanker grt is currently on order [23] about one half of which is VLCC which will probably be designed and built by making a more extensive use of HTS and reduced scantlings than in the past.

Moreover, 3/4 of the actual VLCC fleet is at least 13 years old and the demand is such that most yards (specially Japanese and Korean) are fully booked until well into 1992 and some deliveries are planned for 1993 [24]. It will thus be unlikely to be satisfied unless existing tonnage is used for as long as possible.

From the above, it might be argued that, for new buildings, we now have to choose between two policies; (1) to continue rather prudently as in the past, an approach which may be considered as having been satisfactory on the whole, or (2) to change by adopting a more sophisticated total approach, i.e. by introducing "rational" methods at the design, construction and in-service inspection stages, following the approaches adopted in other engineering fields which are in the vanguard of technical progress.

This "rational" approach should be total, as applying it only to a part of the above stages of the ship's life would not really be worthwhile. Moreover, from a classification point of view, it might imply a special class notation.

One is led to wonder, however, what interest there is in making such a dramatic change for the fleet with low and medium tonnage, since it does not present serious problems and the costs involved would not compensate the benefits gained. Now, the ships of this size represent the larger amount of the total fleet.

The new and "rational" approach therefore might involve in principle the following:

- large vessels
- vessels with a high degree of reliability as, for instance:
  - vessels designed with extensive use of HTS steel
  - vessels intended for dangerous cargoes
  - vessels intended to operate continuously for which any stoppage for incidental repairs should be avoided
- innovative (advanced) concepts.

At this point some words of caution are needed.

Since a reduction and optimization of inspections is implicit in the "new" approach, both during construction and operating life, classification surveys shall be done in accordance with strict procedures and conditions. Consequently, the arrangements and provisions necessary for the surveys, see in particular the special surveys for class renewal, as well as extensive repairs and convertions, would be more costly and time consuming than they usually are at present.

People familiar with surveys will know the degree of cleaning of the spaces and of the structural details needed for visual and non-destructive examinations. Under the new approach, as the results of the inspections will be much more important, the level of cleaning will have to be increased accordingly. From a practical point of view, this may be difficult to achieve. It is easy to imagine for instance what the new procedures mean in terms of time and cost in the case of a class renewal survey for a large vessel.

Therefore, the incidence of cost and time with the new approach, not only at the design and construction stages but also during the vessel's entire life, is to be stressed in order to be realistic in the evaluation of the pros and cons.

Two other important points to be

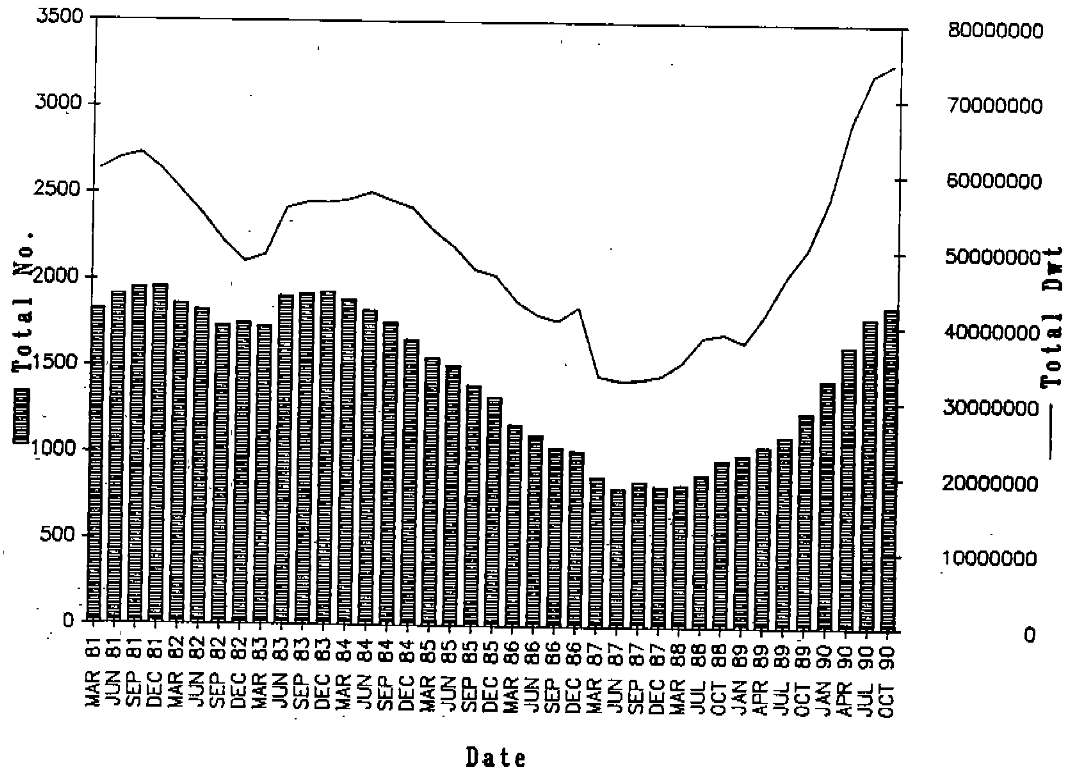

Fig. 2 - All vessel types on order
(taken from [23])

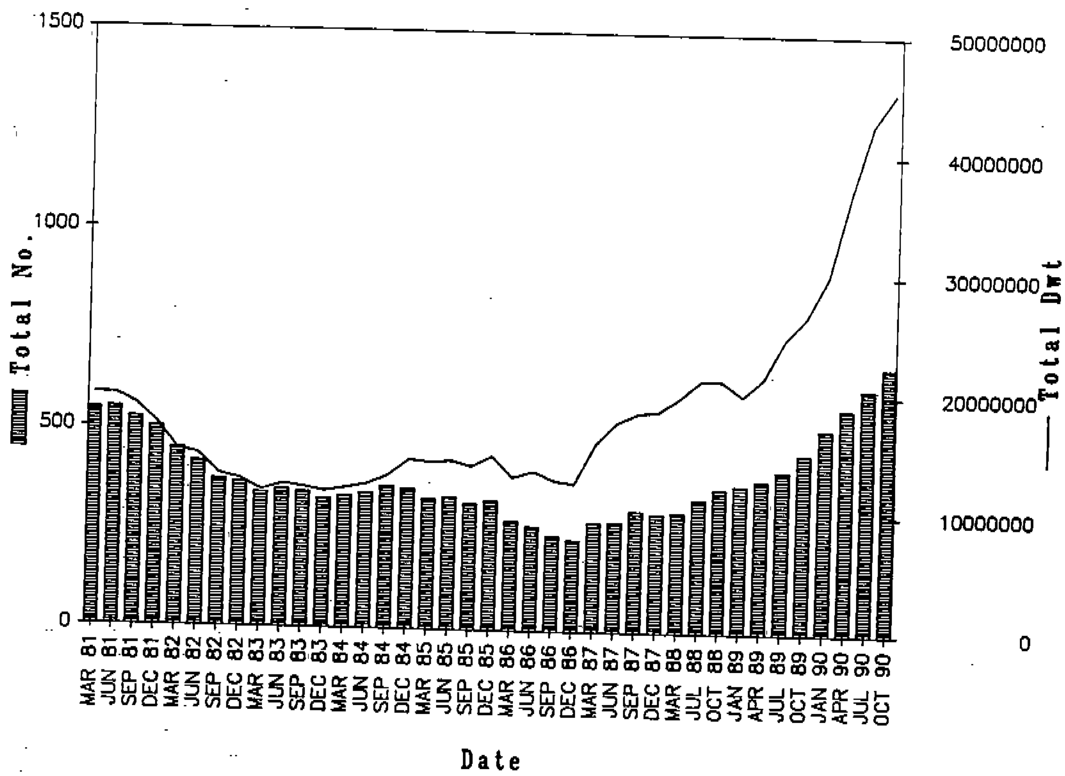

Fig. 3 - Tankers on order
(taken from [23])

mentioned are the influence of efficient on board management and close cooperation between crew, owner and classification society, which are essential for the success of the whole system. In fact, a fundamental requisite is qualified assistance from the crew so that damage and deterioration can be detected early and dealt with.

It seems at this point realistic to ask whether the present level of crew qualification is in general adequate to perform the above tasks.

Another aspect requiring reflection is the extreme care which will be needed in the case of possible repairs (however well a vessel is built and managed, the possibility of repairs should never be overlooked). As in some cases in the past, even the supply of a HTS steel plate to repair a deck represented a serious problem, it is easy to imagine the number of problems which would arise to repair a highly sophisticated structure largely made of HTS steel.

Other examples could be given along the same lines, but this might create a gloomy outlook, which is not the intention the paper wished to convey. The new approach looks promising, it will in the long run be beneficial and it should be attempted, but the problems and responsibilities connected with it must be borne in mind.

As with all new approaches, the transfer of the theory into practice must proceed step by step, following the "trial but no error" policy.

As the Romans used to say " *est modus in rebus* ".

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