Risk-based Inspection System for Collection and Investigating of Structural Data to Improve Design and Inspection Planning

Nabile Hifi\textsuperscript{a}, Nigel Barltrop\textsuperscript{b}\textsuperscript{*}

\textsuperscript{a,b} University of Strathclyde, Glasgow, UK

Abstract

This paper discusses the EU-FP7 Project – RISPECT which provides a methodology that will (on an ongoing basis) combine detailed analysis of long term experience from large numbers of ships with reliability/risk-based analysis methods at both component and whole ship system levels. This will lead to better designs, justifiable risk-based inspection plans and more important defects being found and repaired, in turn increasing personnel and structural safety and a reduction in pollution incidents. The project also provides data structures and classification systems for details and cracks.

Keywords: Risk-Based Expert System; Ship Structural Inspection; Ship Maintenance; Risk & Reliability; Inspection Plan; Ship Maintenance Optimization;

Résumé

Cet article présente le projet EU-FP7 Rispect dont l’objectif est de fournir une meilleure méthodologie qui (sur une base continue) combine l’expérience et expertise accumulées sur le long terme à partir d’un grand nombre de navires, et les méthodes utilisées dans le calcul de fiabilité (Reliability/Risk-Based) pour élaborer des plans d'inspection basés sur les risques justifiables (Risk Based Inspection). Cela conduira à de meilleures inspections, où les défauts les plus importants seront localisés et réparés, ce qui augmentera la sécurité des structures, réduira les pertes de vies et la pollution marine accidentelle. Le projet produit également des structures de données et des systèmes de classification de connexions et de fissures.

Mots-clés: Risque, Fiabilité, Inspection ; Sécurité des Structures ; Connexions ; Fissures ;

\textsuperscript{*} Corresponding author information here. Tel.: +441415484532; fax: +44141552 2879

E-mail address: nabile.hifi@strath.ac.uk.
Nomenclature

RISPECT  Risk-Based Expert System for Through-Life Ship Structural Inspection and Maintenance and New-Build Ship Structural Design

1. Introduction

Ships operate in a severely corroding and metal-fatiguing environment that reduces the strength of the ship structure, which can only be kept safe by regular inspections and repairs of paint coatings, excessively corroded plate and fatigue cracks. The structural strength of ships is a topic of key interest to naval architects and shipbuilders. In general, ships which are built too strong are heavy, slow and cost extra money to build and operate since they weigh more. In contrast ships which are built too weak suffer from hull damage and in some extreme cases catastrophic failure and sinking. Structural failures of ships are, relative to onshore structures, very common and these contribute to the personal risk levels and safety of mariners, high pollution and economic costs.

A good inspection plan is crucial in order to detect structural defects and deteriorations in time and to make decisions about how quickly they must be repaired. Inspection planning may be based on experience (determined by class rules) which will, by default, treat all ships with the same inspection program or on first principal reliability-based methods.

In the first case, only some of the knowledge that could be used to predict structural problems in case of ship-to-ship variation (construction or use) is gained from the data gathered. In the second case, reliability models (methods) can deal reasonably well with individual part but they do not give a good estimate of the overall reliability of the ship and they lack the ‘experience database’ that the experience-based, methodology uses so the reliability models are not calibrated by reality (Hifi et al. 2012a).

The system, which targets the critical structural details in the ship, is intended to be used by the inspection companies, class surveyors, ship managers and ship designers and for the calibration of the inspection planning and reliability models as a decision support system tool to improve the safety of the ship and make inspections cost-effective.

The objectives of RISPECT project are to:

- Estimate the reliability of simple structural components of a ship with allowance for corrosion, fatigue cracking and inspection and repair.
- Provide a standard system for collecting ship structural degradation/performance data.

In addition, the project provides some important outputs that go beyond the present state of the art, including:

- tools that will make the best use of all available structural condition and performance data to plan inspections of existing ships;
- tools that will use the available ship performance data for structural design within a goal based design approach;
- a standard database structure that can be used by the industry – eventually on a continuous basis for all ships - to gather the performance related information that is needed as a data source for this methodology;
- tools for assessing structural loads, stresses and strength simply but effectively;
- tools that calculate consequences of local failure and overall hull “system” reliability;
- tools for determining fleet reliability (e.g. the probability of any one tanker from a fleet having a serious structural failure in any year);
- a methodology for assessing the quality (in statistical terms) of the conclusions drawn and recommendations made using the tool; and
- tools based on the S-N fatigue analysis and expert system methodologies to provide a check on the primary methodology used within the project.

The flow chart of the RISPECT Engineering calculations (Barltrop 2010) is given in Fig. 1. It gives the information on what is being stored in the Database, the links between the Database and each engineering calculation programme, the control of the input and how the Central Statistical Database (CSD) is being used in the project.
The system is built from multiple programs connected to each other and consists of:

- Hydro-Static/Dynamic Pressures & RAOs
- Global and Member Forces
- Extreme and Fatigue Global & Member Forces
- Local Structure & Crack Calculations
- Coating Breakdown Anode Loss & Corrosion
- Structural Strength & Reliability Calculation results
- System Reliability Calculation results
- Risk Calculations
- Strength & Fatigue Check (and other checks on the methodology)
- Fleet Reliability
- Fleet Risk

For more details on the functionality of each part of the system, the reader is referred to (Hifi et al. 2012a).

This paper discusses some of the results of the Rispect methodology applied to a 50000 tonne displacement double hull product tanker. The tanker model was set up using both a complete, single model, finite element approach and a “parallel” hierarchical model.
2. Rispect Calculation Methods

To estimate the reliability of simple structural components of a ship, two types of calculations were planned to be performed (Barltrop et al. 2010; Hifi et al. 2012b):

*Calculations to assist with computing calibration factors (1)*

For all inspected locations from launch and up to the times corresponding to the inspections, the structural degradations (anode and coating degradation, corrosion wastage, fatigue cracking and buckling) are calculated. These results are compared with the findings from inspection to compute calibration factors for future calculations. These calibration factors are held in a ‘CSD’.

In this context, the calibration factors are the parameters used to correct the mathematical model used for the deterioration prediction of the structural component or member. The factors are calculated using the predicted data and the recorded or inspection data (Hifi et al 2012c, Hifi et al. 2012d).

*Calibrated calculations (2)*

Using the structural degradation prediction models with the stored calibration factors, the results from new or previous survey are extrapolated in time over the required calculation period. Mean, standard deviation and confidence factors of the expected deterioration are calculated. These are used for inspection planning and risk analysis.

It is not necessary for all users to use the same analytical models. However each model requires different calibration factors.

3. Observations From RISPECT Application

3.1. Setting up the structural models

However the model is set up it is time consuming. The tanker model was set up using both a complete, single model, finite element approach and a “parallel” hierarchical model. The hierarchical model was originally planned but, on starting RISPECT, it was decided instead to use a single model approach with the commercial Maestro program (Barltrop et al. 2013b). A major problem with the use of the Maestro software was the time taken to interface the commercial software with RISPECT, especially because the backing file system for Maestro changed completely during the RISPECT project. There was also the need to be able to relate the Finite Element (FE) results to other data such as inspection data. This was achieved by the database intelligently matching results on the basis of the coordinates of the members and this was the approach used to incorporate Maestro results within the database.

Owing to delays in interfacing the Maestro models a hierarchical (3-stage) “parallel” approach was also used. This was based on modified but essentially pre-existing in-house software:

- The global model provided estimates of global structural responses (hull girder bending moments etc.), rigid body motions (e.g. Roll angle and heave acceleration) and relative water surface elevation on the side of the ship. For this work long term statistics of 11 variables at 7 locations along the length of the ship, including the full (77x77) correlation matrix was calculated.
- The x-section model allowed the calculation of local stresses from e.g. the global bending, shear and torsion of the global model.
- The tank model enabled the calculation of tank bending behaviour (in the flats and frames) and the local stiffener bending moments as all flats, floors and web frames and longitudinal stiffeners were modelled. Forces in transverse stiffeners were also estimated from the pressures applied to the model.

The results of the three analyses were then combined as shown in Fig. 2.
Using in-house software it was straightforward, though slightly laborious, as the structural model was built, to label each part of the structure with its RISPECT identification system (based on Frame, Port/Starboard/Centre, Area, Stiffener number, Stiffener end). Then if all other, particularly inspection and repair, information was input using the same identification system there would be no need to match data on the basis of geometry. In practice it is very difficult to ensure external data arrives in the correct format so the ability of the RISPECT system database to match data that arrives with different reference systems is extremely useful.

It is clear that a purpose built FE program needs to be built into RISPECT system, the hierarchical process is good for tankers but more difficult to apply to bulk carriers and other open box hull forms such as container ships and gas carrying ships. Also if analysis of serious, e.g. collision, damage is to be included (subject to future development) then it will be much easier to model damage to a single overall FE model than to three hierarchical models.

3.2. The RISPECT identification system

Each stiffener at any frame is uniquely identified by the frame number, the area number, whether it is port, starboard or central, the stiffener number and the end number. The frame numbers are as defined on the ship’s drawings. A stiffener on that frame or between that frame and the forward frame is assigned that frame number. Area numbers were allocated on the basis of likely panel buckling behaviour (although stiffener, not stiffened panel behaviour is presently included in the system). Stiffener numbers may be on the ship’s drawings or may need to be assigned for use within RISPECT.

3.3. Hydrodynamic and structural analyses

The hierarchical models lent themselves to a coupled global hydro-elastic analysis: i.e. the global wave loading response and structural response are calculated in the same analysis with a coupling of the two analyses. This is particularly useful for including “springing” within the analysis. (Springing is a dynamic response that occurs when the encounter frequency of the waves corresponds to a hull girder natural frequency.) “Whipping”, the dynamic response from a bottom impact was not included in either the hierarchical or single models although again it is easier to include whipping in a hydroelastic beam model.

Overall therefore, future options for including springing and whipping would still include the consideration of a separate hydroelastic model.
3.4. Generation of global and member long-term response statistics

This was done by specifying the trading route (in this case world-wide trading) and applying spectral analysis to enable the calculation of the statistical response in all the sea states, directions and speeds likely to be encountered over the life of the vessel. The calculations here were performed for a new ship but the calculations could be based on the known trading to date and the expected trading for the future. The amount of spectral analysis required was considerably reduced by assuming that, for any mean zero crossing period: \( T_z \), the water surface elevation spectra always had the same shape. This allowed one spectral analysis for any Speed/Sea-state \( T_z/\text{Sea-state relative direction} \) to be scaled to any required particular significant wave height. In reality spectral shapes will differ but this is a small approximation for a very large saving in computational time.

A \((77x77)\) correlation matrix was then calculated between the \((11x7)\) values described in 4.1 above. This was calculated from the variances and cross variances of all pairs of normalized values. (Because correlations are dependent on the relative size of the variables, and the correlations are only important when the correlated quantities make a similar contribution to the failure mode, which is not known at this stage of the calculation, it is preferable to correlate the values normalized by their standard deviations.) These correlations are used both in the single point “component” reliability calculations, where they take phasing into account and in the system reliability calculations where they reduce the failure probability in comparison with the assumption of independence between each location on the ship.

The global Weibull distributions and correlations were then converted to member (i.e. stiffener and plate) force Weibull distributions and, for any member the correlations of the various forces at each end and the middle are calculated. This is done from the global distributions and correlations using influence factors derived from the hierarchical models and using empirical rules for adding Weibull distributions that have been developed within the RISPECT project.

3.5. Quantity of information

The detailed results from the RISPECT system are potentially very extensive. In the cargo tank length of the ship, there are about 14000 structural connections (280 on each frame and 49 frames). At each connection, for RISPECT analysis purposes, there are typically 18-29, say on average 24, possible crack types. Overall therefore there are about 336000 possible cracks to be checked for every year over maybe 20 years.

This causes two possible problems:
- It could result in excessive computer time
- It could overload the RISPECT user with data.

Graphical information is easier to absorb quickly than lots of tables of numbers, so the initial information about problem areas identified by the program is given by colour coding on plans of those areas. In reality the problem locations will commonly be lots of points on the structure but it is more helpful to show lines or bands of colour to draw attention to the important areas. Even if yellows and reds are used to identify areas of low reliability that may need further attention, there are a number of options for the colour coding itself, eg.:
  - Colour contours proportional to stress.
  - Colour contours proportional to failure probability.
  - Colour contours proportional to the \( \log_{10} \) of failure probability.

In this application, option ‘c’ that highlights the areas needing attention. However a designer may prefer option ‘a’ because that could give a better idea of where additional steel, or better structural details, are required, or where some reduction in steel may be possible.
3.6. Decision support

At present, once the analysis has identified the problem areas it is for the ship management naval architect to look in detail at the available data (failure probabilities and sensitivities) and to use the sensitivity information to help to choose an appropriate course of action (e.g., in ideal cases, increasing stiffener sizes at the design stage or increasing coating/crack inspection and repair during operation). However practical maintenance cases may require some combination of structural improvement, changes to inspection and possibly, changes of use. For design there may be a question of whether designing the ship to operate in severe environmental conditions for its whole 20 year life is necessary. If that is definitely required then the structural details and coating maintenance can be determined to obtain the required reliability throughout the required life, but there will be an additional cost.

Whilst not presently provided within the RISPECT system this case study has suggested that useful additional guidance, in which improvement options were ranked, could be provided to the naval architect, so the system could effectively suggest that particular structural improvements or changes to inspection plans would solve the identified problems.

4. Results and Discussion

This case study applied the RISPECT methodology to tanks 3, 4 and 5 of the tanker with the extent of the reliability and risk analysis.

4.1. Acceptable failure probability

When assessing the results they need to be compared with an acceptable failure probability. The acceptable failure probability depends on the consequences and most of these need to be considered at whole ship (system) level rather than at the level of individual component failures. In the system calculation costs of repairs as well as failures and correlating effects are taken into account. For repairs there will be a trade-off between (inspection intervals, quality and recoating decisions) and (cost of recoating versus cost of steel renewal at a later date). Cost of crack repairs in this example is low.

The critical cost of fracture leading to a pollution incident is related to a high consequence but with a relatively low probability, although by year 20 the failure probability at component level is in the region $10^{-3}$ to $10^{-2}$ which is uncomfortably high. The overall risk (where risk is defined as probability x consequence) at system level can only be calculated once the component reliability calculations have been performed. The risk can be minimized and the associated system failure probability can be related back to the component failure probabilities. This could be done in several ways e.g. a target maximum failure probability could be specified or a target proportional change in the higher failure probabilities that are affecting the overall system reliability calculation could be specified.

A potentially useful output of the system reliability calculations would be the sensitivity of the system failure probability or risk to changes in the reliability of the component parts. It is also possible that an operator of a number of vessels might want to further reduce the risk owing to a commercial consequences that are only indirectly related to the failure (oil companies lose retail sales when they have an incident). This could demonstrate that a higher reliability/lower failure probability is desirable for each ship in the fleet and therefore for the individual structural details on the ship. The case study is extended to system reliability and risk in the separate system reliability; it does not extend to these commercial considerations but the calculation of fleet risk.

From the discussion above it can be seen that the decision making associated with the reliability and risk analysis involves some iteration. The component reliabilities and risks feed into the overall system (and optionally the fleet) reliability and risk calculations. If the system reliability is unsatisfactory then that will require modifications to the component reliabilities (by change in design or maintenance). For this example it is assumed that, at this stage of the iteration the target component reliability is $5 \times 10^{-4}$. This roughly corresponds to a target $\log_{10}$ of failure probability of -3.5 or a $\beta$ value of +3.5. (Note in general $\beta$ is not $-\log_{10}(\text{failure probability})$).
4.2. Structural details

The conventional connection between a longitudinal stiffener and a transverse frame involves the longitudinal stiffener being welded to the transverse frame stiffener, as shown in Fig. 3. This has led to many fatigue problems in the past, both in ships and steel bridges. Many bridge engineers have avoided this type of connection for 30 years, however only recently are naval architects doing likewise. The designers of the tanker being analysed here have frequently avoided the connection in the side shell by running frame stiffeners vertically rather than horizontally. Unfortunately there is still a need to provide some transverse “tripping” support to the transverse frame stiffeners. When this support cannot be provided at flats, then transverse stiffeners are provided; welded to the longitudinals they have an adverse effect on the fatigue life. This tanker has such details in the side shell along stiffeners 22 to 27 and 34, as well as in the deck and inner and outer bottom. The stiffeners intersecting the frame stiffeners generally have the lower reliabilities and this report concentrates on those stiffeners.

![Fig. 3 Connection of Longitudinal and frame stiffeners](image)

4.3. Available results

Probabilities and consequences

The results presented here provide:
- Estimates of what coating breakdown, corrosion and cracking might be found during inspections, including amount of repair that can be used to estimate repair costs.
- A “probability of local separation” is also given. This indicates a change in load paths and when this probability is high it is likely to result in a poorer accuracy of other quoted values.
- Estimates of the probabilities of various leaks and quantities; cargo to the sea clearly has pollution consequences. Other leaks may be relatively unimportant, although an oil to ballast tank leak might possibly result in an explosion.

Examples of the above probabilities are shown in Fig. 4.

![Fig. 4 Examples of calculated probabilities for a specific location](image)

Within RISPECT, failure probabilities are also available as beta values. Beta represents the number of standard deviations from the mean behaviour that corresponds to the failure. So a beta of 2 corresponds to a failure probability of 2.3%. In this report the probability values only are considered. However for some calculations the beta values are more useful.
Sensitivities
The sensitivities of the calculated probabilities to input assumptions have been calculated. The sensitivities are presented as the change in failure probability for a one standard deviation change in the parameter (e.g. yield stress, fracture toughness, still water loading). These sensitivities are necessary for the methodology used in the system reliability calculations. The sensitivities are useful for use with CSD calibration factors for adjusting to minor updates in the calibration values without requiring a complete and time consuming rerun of the reliability analysis every time the calibration factors change. Detailed results of the sensitivity analysis are subject to future publication.

The sensitivities also give an impression of the important parameters affecting any particular component. A high sensitivity compared with the failure probability indicates that parameter is having an important effect on that failure probability. This allows some element of checking whether results are sensible and also indicates:

- to designers how a design might be improved, and
- to maintenance engineers how reliability might most conveniently be increased.

At present the sensitivity results have to be studied to determine the importance of the different parameters. As a future enhancement, the guidance available from the sensitivity results could be extracted and presented in a simpler way. Also, for use by the designer/engineer, the sensitivities could be more conveniently provided in terms of a unit change of the parameter, instead of a unit change in the standard deviation of that parameter. However, when using the sensitivity information for assessing the effect of changing the mean value of an input quantity it should be noted that, owing to the non-linear relationships, these sensitivities are only valid for the specified change, usually of one standard deviation in the quantity. For automatic calculations it is best to use the beta calculations and beta sensitivities instead of the failure probabilities. These will be better behaved values and will respond more linearly with changes to the input values. It is anticipated that most ship managers will not be comfortable with beta so the programs could use the beta values internally whilst presenting results in terms of failure probability externally.

5. Conclusions
The component reliability calculation methodology and methods of using the methodology at both the design stage and for maintenance planning have been shown and the methodology seems to work satisfactorily.

The full reliability calculations on the ship structure are time consuming to perform. However the amount of calculation can be reduced by identifying critical crack types and locations for checking. In the longer term increases in computer speed, or parallel processing, coupled with software that is optimised for rapid running rather than system development and checking should make it unnecessary to take these short cuts.

The study demonstrated that the sensitivity data was very useful for deciding what options were worth pursuing to solve any particular reliability problem. Detailed results of the sensitivity analysis are subject to future publication.

The developed system could be enhanced to use the sensitivity data to automatically propose design or inspection modified strategies for the ship designer to consider and refine using detailed reliability analysis. Rerunning the reliability calculations at critical or representative locations was found to be preferable to using the sensitivity data to determine the precise changes in reliability. This was because the rerun at a limited and targeted number of locations is quick, it gives more detailed information and it does not make the linearizing assumptions that are required when using the sensitivity data.

This study also raised a question about the sub-division of calibration information: it may be more useful to distinguish in the calibration between local pressure loads and overall hull girder loading. Also it is common to find different factors for extreme hogging and sagging, so this should be built into future versions of the RISPECT system.
Whilst the methodology is useful in providing a theoretical reliability analysis of a ship, at component and system level, the largest benefits of RISPECT will come from using the CSD-processed measured and inspection data within the reliability calculations. The calibration values that result from this will gradually change with time.

The target reliabilities used within the component reliability analysis will be determined by the risk analyses performed at the system level. There is inevitably some iteration required between the component and system calculations. This will be particularly important when the system is first applied to any specific ship. Once the system has been run it is anticipated that the component target reliabilities will not change too rapidly so the iteration will not be required very frequently.

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