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Fatigue Damage in the Expansion Joints of SS ROTTERDAM

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After 38 years of satisfactory service, the Holland-America Line sold her flagship “ss ROTTERDAM”. Although promised to Lloyds, studies and tests made during construction on the expansion joints were never published. This PRADS’98 Conference is a good occasion to report on these now. Moreover, the behaviour is placed in the light of fatigue assessment in retrospect.

1. INTRODUCTION

In 1959 the Rotterdam Dockyard Company delivered the 200 m passenger ship ss ROTTERDAM to the Holland-America Line, HAL [1]. Until last year the vessel was operated by the HAL. She now sails under the name REMBRANDT for Premier Cruises.

The vessel is one of the first fully welded passenger ships.

At the time of building of the ss ROTTERDAM, most passenger ships had expansion joints. However, much research was carried out on incorporating the superstructures in the strength of the hull girder [2, 3, 4, 5, 6]. A full-scale test was already made in 1913 by building the CALGERIAN with and her sister ship ALSATION without joints [7, 8].

The yard decided to fit four expansion joints, based on five arguments:

1. At the time the scantlings had to be decided on, the arrangement of the superstructure and its contribution to the strength was not known.
2. The risk of cracks in the superstructure at uncontrolled spots was

considered to be larger than at the joints.

3. The expansion joints fitted on the ss NIEUW AMSTERDAM, built by the same yard in 1938, gave satisfactory results, although cracks did develop.
4. The construction of this ship was not a routine job for the yard; therefore a proven design was favoured.
5. There was no financial pressure to save building costs by leaving out the joints.

After commissioning in 1959, the vessel sailed on the North Atlantic service in the summer and made cruises in winter time. In April 1963 a crack was reported at the joints on frame 138/139. After repair and modification no cracks were reported since. The ship's logbooks are still available. From these it was possible to draw up a history of sea states and headings to which the vessel had been subjected until the crack occurred. With the current computational tools a fatigue damage analysis was carried out on the expansion joint. The results of this research are reported in this article.

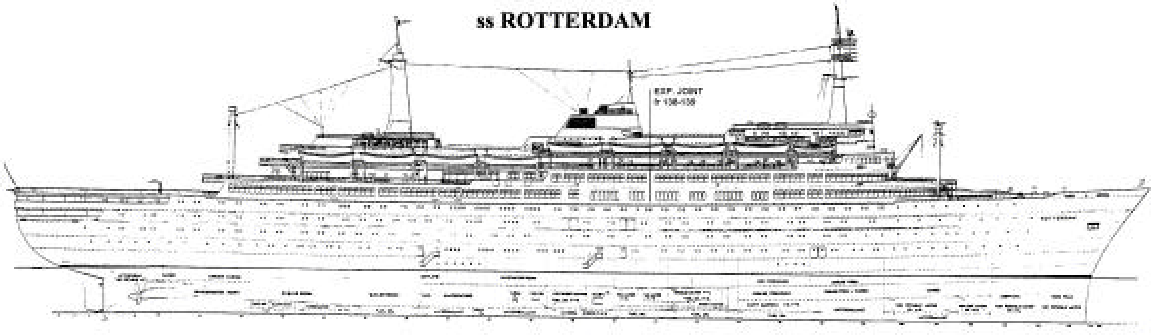
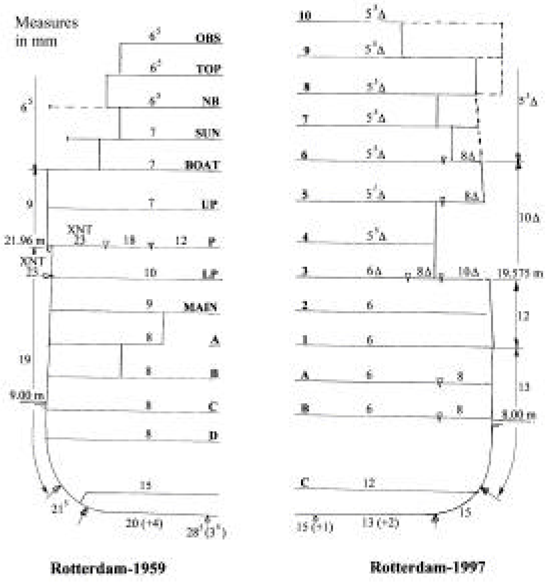


Figure 1 Side View of ss ROTTERDAM

2. THE SHIP

Figure 1 shows a side view of the ship and Figure 2 gives a general impression of the midship section. For comparison the cross section of the new ROTTERDAM-1997, built in Italy, is shown as well. The 1959 ship has the promenade deck (P) as strength deck. The plating of the 1997 ship on deck 3 and above is of high tensile steel, while the superstructure up to deck 8 forms part of the hull girder. It is remarkable to see that plate thicknesses have been reduced considerably over the years. The ROTTERDAM-1959 is fitted with transverse frames, while the ROTTERDAM-1997 is fitted with high tensile longitudinal frames. Owners extra's are indicated in brackets. Both ships are classified by Lloyds Register of Shipping. The sectional modulus of ROTTERDAM-1997 at deck 8 (34.80 m above base) is almost equal to the section modulus of ROTTERDAM-1959 at the promenade deck P (21.96 m above base).

Figure 3 shows a detail of the expansion joint as applied just above the promenade deck. Initially bolt holes were present in the edge strengthening bar. At the repair and modification in 1963 stud bolts were welded on the bar.



XNT special notch tough		Δ steel 500 N/mm2
Lpp	198.12 m	202.00 m
B	28.65 m	32.25 m
T	9.00 m	8.00 m
∇	30400 m3	32500 m3

Figure 2 Cross-Section ROTTERDAM 1959/1997

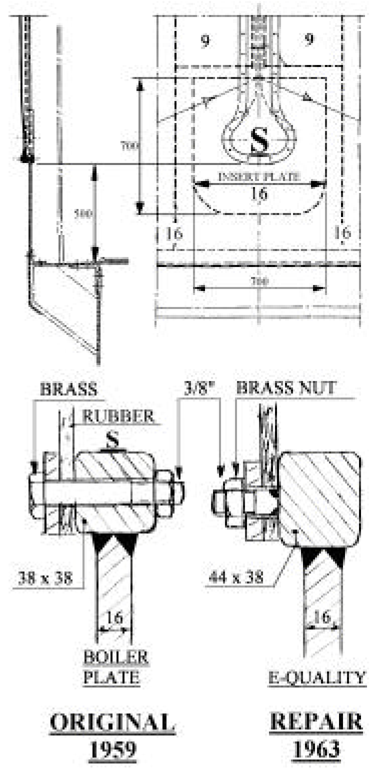


Figure 3 Expansion Joint Detail

3. APPLIED ANALYSIS

A fatigue calculation has been carried out in retrospect. The procedure as described below has been followed.

1. All logbooks from the maiden voyage up to the first reported crack at the expansion joint were analysed.
2. The ship’s behaviour in seaway was calculated by applying a general purpose ship motions prediction computer program. This analysis yielded a set of vertical en horizontal hull bending moment frequency response functions (*FRF*) for the cross section at frame 138/139.
3. This set of *FRF*’s was used to calculate the stress spectrum in the promenade deck at the side during each watch of 4 hours. The environmental conditions and the ship speed were assumed to be constant during each watch.
4. From each stress spectrum the cumulative probability distribution of the stress range was calculated by assuming a Rayleigh distribution.
5. For each spectrum the number of zero up-crossings was determined.
6. The number of cycles at 23 stress ranges was calculated
7. The number of cycles for the considered stress ranges for each watch were finally added.
8. Next, the number of cycles per stress range were divided by the “required” number of cycles up to damage for the given stress range.
9. Finally the individual damage ratios were added up, yielding the cumulative damage *D*.

Items 8 and 9 describe the Palmgren Miner approach for calculating fatigue damage in a structural detail [10].

4. BEHAVIOUR IN SEAWAY

To calculate the behaviour of the ship in the experienced wave conditions until cracking of the expansion joints, the computer code SEAWAY of the Delft University of Technology [9] has been used. This program calculates the loads and motions of ships in waves in the frequency domain by the linear strip theory method. Depending on the shape of each cross section, a 10 parameter close-fit conformal mapping method or Frank's pulsating source method is used to calculate the 2-D potential coefficients.

After taking into account the forward speed effect, the coefficients of the equations of motion in the frequency domain are obtained by a longitudinal integration of the 2-D values. The presence of bilge keels and fin stabilisers has been taken into account. Bretschneider wave energy spectra are used to obtain statistical data on motions and loads in irregular waves.

The ship's under water hull form is given in Figure 4.

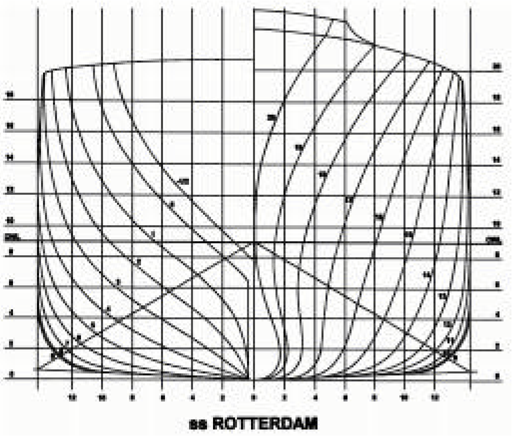


Figure 4 Body Plan ss ROTTERDAM

The distribution of the mass along the ship length is shown in Figure 5.

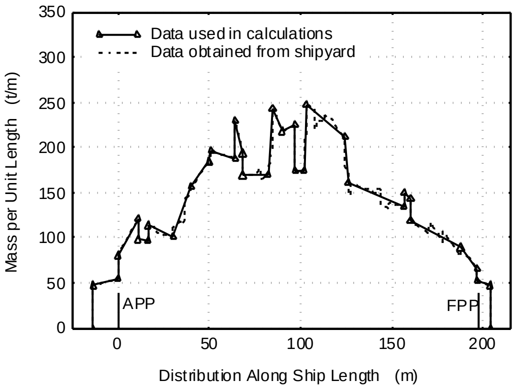


Figure 5 Mass Distribution ss ROTTERDAM

Further input for the hydromechanical calculations were:

Draught (average)		8.86 m
Metacentric height		1.25 m
Radii of inertia	k_{xx}	11.45 m
	k_{yy}	51.80 m

The data from the logbooks were taken per sea watch, i.e. 4 hours. The time span investigated starts in September 1959 and continues until April 1963. In total 4634 observations were recorded. Figure 6 shows the exposure of the vessel to sea states during the considered period.

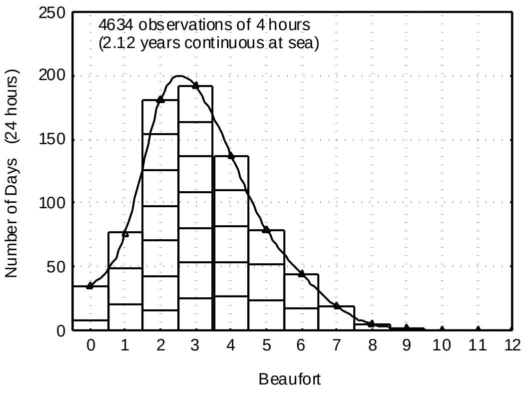


Figure 6 Exposure of Vessel to Sea States From 1959 Till 1963

It can be seen that the vessel has not often been subjected to very heavy weather. For each period a Bretschneider sea spectrum is assumed based on the observed sea state. From this spectrum and the heading of the ship, the horizontal and vertical bending moment in the ship's hull in way of the expansion joint were calculated. Because of the closed cross section, torsion could be ignored. Next, they were divided by the respective section moduli and added, thus yielding a spectrum of longitudinal stresses in the promenade deck at the side. As illustration, Figure 7 is included to give an impression of stresses in the promenade deck.

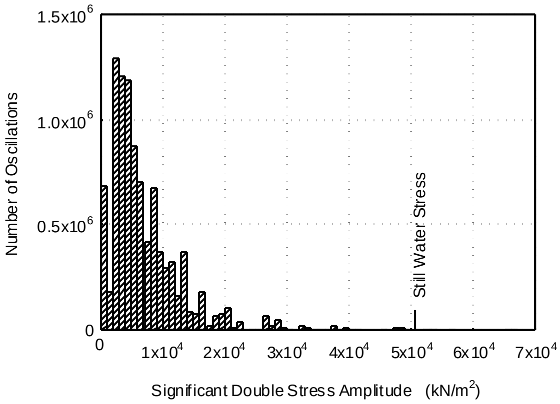


Figure 7 Stress Levels Versus Number of Stresses in the Promenade Deck

The area properties m_{0s} and m_{2s} of the stress spectra were used as input for the fatigue analysis.

5. STRESS ASSESSMENT

The cracked expansion joint is situated at frame 138-139 (0.55 Lpp from APP), 500 mm above the promenade deck. Due to its geometry, the stress at the bottom of the expansion joint will be larger than the stress level in the promenade deck.

Prediction during design.

During the design of the ship a Stress Concentration Factor *SCF* = 3.5 has been estimated based on analytical conside-rations.

Measurements during launching.

During the launch of the vessel 1958 the Ship Structures Laboratory of the Delft University of Technology, DUT, and the Netherlands Organisation of Applied Scientific Research, TNO, carried out strain measurements on several spots in the vessel [12]. The bottom of the expansion joint and the promenade deck were included. Stresses during launching were 40% of the stresses calculated for the design wave (see Figure 8).

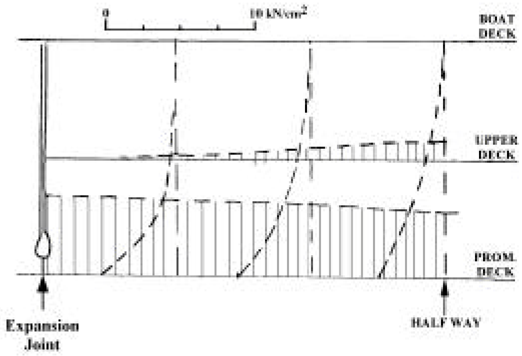


Figure 8 Stresses in Promenade Deck and Superstructure Side

The major conclusion of the measurements was that there was only a slight increase in the stresses in the strength deck below the expansion joints. A stress concentration factor *SCF* = 4.4 was found in the bottom of the joint (point S in Figure 3), which was higher than expected. It was realised that here the fracture strength of the steel 41 would be surpassed, as Lloyds set for this ship a maximum allowable hogging stress in the strength deck of 125 MPa.

The section modulus at the strength deck, including owwners extra's was 20

% higher than required by Lloyds. Therefore a crack might occur after sufficient heavy loading. This was not considered to be a risk for the hull, as it would not lead to any major rise in the stress in the topsides. Both the stringer plate and the sheer strake are of special notch tough (XNT) steel. The riveted deck stringer angle and the angle bar connecting the side plates, work as crack arrestors while spreading the forces over the length.

An attempt was made to correlate the measured stresses during launching with the stresses from the launching calculations.

Two differences were found:

1. The measured maximum sagging stress at the point of uplift as measured was smaller than calculated.
2. The hogging stress measured while the ship was fully afloat proved to be smaller than calculated.

The first difference is mainly due to the effect of the presence of breaking shields and maybe also due to a difference between effective and calculated section modulus. The second difference is due to a hogging stress while the ship was still at her berth. At this position strain gauges were set to zero. This hogging was probably due to the weight distribution over the flexible berth and stresses caused during welding of the hull.

Recent finite element calculations.

An attempt has been made to estimate a stress concentration factor, *SCF*, based on both a coarse mesh and a fine mesh finite element calculation.

For this purpose the environment of the expansion joint has been modelled with plate elements capable of describing membrane stresses. The analysis is limited to in plane deformations only. The lower edge of the model is at promenade deck level.

The left hand side of the model and the lower edge are subjected to an imposed horizontal displacement equivalent with a strain of 238 microstrain, i.e. a stress level of 50 MPa. The lower edge is restrained in vertical direction. The right hand side edge of the model, between bottom of the joint and the promenade deck is restrained in horizontal direction. The upper edge is subjected to an imposed displacement and rotation, taken from the strength analysis carried out by the yard. Figure 9 shows a contour plot of the calculated stresses.

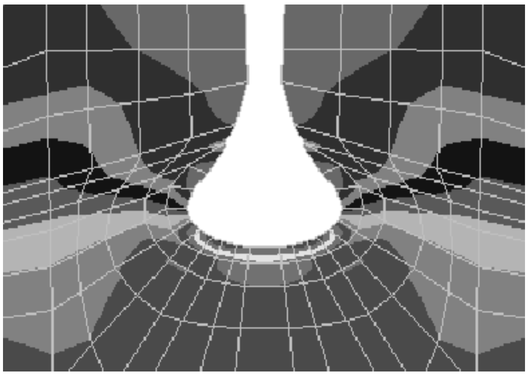


Figure 9 Stress Contour in Way of Expansion Joint (Frame 137-138), Coarse Mesh.

The stress increase between lower edge (deck level) and the bottom of the joint was similar in both cases: *SCF* = 2.7.

Review of *SCF*’s

A brief review of the obtained stress concentration factors at the bottom of the expansion joint is given in Table 1.

Method of assessment	SCF
Prediction during design	3.5
Measured during launching	4.4
Recent FE calculation	2.7

Table 1 Assessed Stress Concentration Factors

These factors, determined at the centre line of the expansion joint, do not include the effect of the presence of bolt holes.

It is noted that the *SCF'*s do not match very well. The effect of mesh size was checked but proved in this case negligible. The effect of the stress built up between the expansion joint (Figure 8) proved to contribute substantially to the stress increase in the joint.
In case of the presence of bolt holes an additional *SCF* must be applied of 3, see Figure 10 obtained from ref. [10].

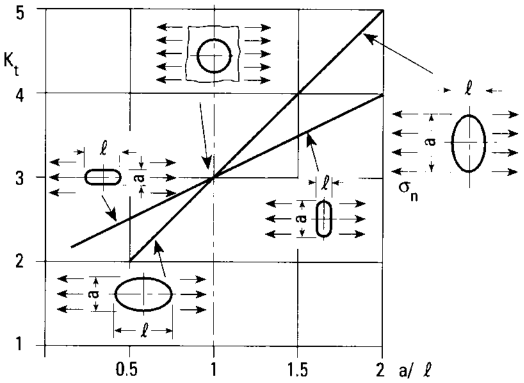


Figure 10 *SCF* for Cut Outs From [10]

Therefore the actual *SCF* to be used in a fatigue assessment should lie between 5.1 and 13.2!

6. FATIGUE ASSESSMENT

For the considered life period of the vessel the number of cycles at 23 stress levels ranging from 1 Mpa to 1000 Mpa has been determined. For this purpose cumulative probability density functions were assumed, based on the stress spectra as determined for each watch.
A Rayleigh distribution is assumed which could be characterised by the area m_{0s} of the stress spectra. The number of cycles is calculated by dividing the 4-hour watch period in seconds, by the average zero up-crossing period (based m_{0s} and m_{2s}.). The number of cycles for the considered stress ranges for each watch were finally added, yielding a final set of pairs with stress range and number of cycles. Next, the number of cycles per stress range were divided by the "required" number of cycles up to damage for the given stress range. Thus damage ratios per stress range were obtained. Finally the individual damage ratios were added up yielding the damage ratio *D.* A value larger than 1.0 implies fatigue damage and *D* lower than 1.0 implies no damage.
Without applying any *SCF* the result is shown in Figure 11. This diagram is valid for the stresses in the promenade deck. From [11] an S-N curve (curve D) has been taken, considered to be valid for the structural detail under consideration. This curve shows the number of stress cycles "required" to obtain fatigue damage at any stress level.

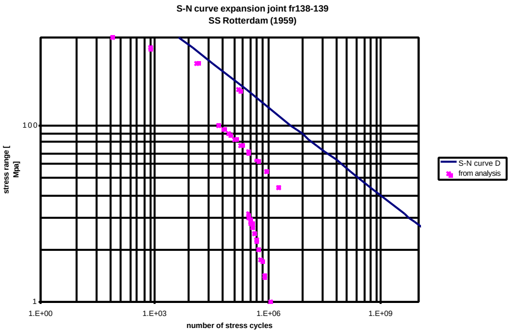


Figure 11 Stress Level Versus Number of Stress Cycles (S-N Curve)

The fatigue assessment on the bottom of the expansion joint. was carried out with four different *SCF* values. Table 2 shows the results.

SCF from	***SCF***	***D***
Analytical considerations x 3	10.5	2.65
Measured (launching)	4.4	0.19
Measurement x 3	13.2	5.27
FE-calculations x 3	8.1	1.22

Table 2 Fatigue Assessment Results

Note that a fatigue crack occurs when *D* is larger than 1.0. A crack is to be expected much earlier than the considered period, when the *SCF*'s from analytical considerations or measurements are applied. When using the SCF from the FE analysis a fatigue life is found which is nearer to the actual reported life. When the *SCF* increase due to the presence of the bolt hole is discarded, no damage is expected. It is interesting to note that the effect of the presence of a bolt hole is decisive. Survey reports of Lloyds were scrutinised from 1959 till 1997.

The joints did not give any problems after the modification in 1963.

The fact that the crack developed in the first years and none afterwards will have had three probable reasons:

1. The built in welding stresses were releaved by heavy loading of the hull.
2. The detail of the joint was improved deleting bolt holes.
3. The ship was taken out of the Trans-Atlantic service in 1969 where after she was mainly cruising in good weather areas.

7. DEVELOPMENTS

Nowadays all passenger ships are built without expansion joints. On some, high tensile steel is used. Apparently classification societies are satisfied with the performance of the ships as the surveyors don't report cracks. The fact that cruise ships predominantly sail in fine weather areas will have its influence in this matter. With the enormous growth of the market cruising will become world wide. Notwithstanding weather routing, the ships will have to sail to their destination and may face heavy weather close to port. Recent examples are QUEEN ELIZABETH 2 in September 1995 and the ROTTERDAM in April 1997 close to the U.S. East coast, where both ships suffered damage. This is not too serious as long as only bulwarks and front bulkheads are involved. Plastic deformations and cracks in the hull girder must be avoided by careful analysis of critical spots including fatigue assessments. One should bear in mind that high tensile steels do not have any higher resistance to fatigue than mild steel.

Full scale measurements on the cruise ship ROYAL PRINCESS built in Finland give an good picture of the contribution of the superstructure to the strength of the hull [13]. Further reference is made to interesting papers by Mr. M.J. Gudmunsen [14], Mr. Violette and Mr. Shenoi [15].

8. CONCLUSIONS

The assessment of a stress concentration factor *SCF*, in the bottom of the expansion joint, based on finite element calculations shows a difference with an earlier analytical assessment and strain measurements during the launch of the vessel.

The effect of the bolt holes in the strengthening bars in the expansion joints prove to be paramount with respect to fatigue damage.

9. ACKNOWLEDGEMENTS

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REFERENCES

1. “D.S.S.Rotterdam - Holland Amerika Lijn”, Extra Edition of “Schip en Werf” - September 1959 (in Dutch).
2. Chapman, J.C.: “The Interaction between a Ship’s Hull and a Long Superstructure”, Trans. R.I.N.A. 1957.
3. Johnson A.J.: “Stresses in Deck-houses and Superstructures”, Trans. R.I.N.A. 1957
4. Caldwell, J.B.: “The Effect of Superstructures on the longitudinal Strength of Ships”, Trans. R.I.N.A. 1957.
5. Vasta, J.: “Structural Tests on the S.S. President Wilson” , Trans S.N.A.M.E. 1949.
6. Vasta J.: “Full Scale Ship Structural Tests”, Trans S.N.A.M.E. 1958
7. Foster King, J.: “On Large Deck-houses”, Trans. I.N.A. 1913.
8. Montgomery, J.: “The Scantlings of Light Superstructures”, Trans. I.N.A. 1915.
9. Journee J.M.J. (1992), “SEAWAY – DELFT, User manual of release 4.00”. Thechnical Report 910, Delft University of Technology, Ship Hydromechanics Laboratory, The Netherlands.
10. Fricke Dr. W., Petershagen Prof. Dr. H., Paetzhold Dr. H. (1997), “Fatigue Strength of Ship Structures, Part I: Basic Principles”. GL-Technology Number 1/97, Germanischer Lloyd, Hamburg.
11. Classification notes Note No. 30.2., “Fatigue strength analysis for mobile offshore units”, Det Norske Veritas, august 1984.
12. “Spanningsmetingen gedurende de Afloop van het S.S.ROTTERDAM”, Laboratorium voor Scheeps-constructies Rapport no 58 - 30.10.1950, University Delft (in Dutch).
13. Fransman, J.W.: “The Influence of Passenger Ship Superstructures on the Response of the Hullgirder” Trans. R.I.N.A. 1988.
14. Gudmunsen, M.J.: “Some Aspects of Modern Cruiseship Structural Design”, Lloyd Register of Shipping- May 1996.
15. Violette F.L.M., Shenoi R.A., “On the fatigue performance prediction of ship structural details”, RINA paper No. 4, Spring Meeting 1998.