LESZEK KONIECZNY, D.Sc.,N.A.
GRZEGORZ LITWINIENKO, M.Sc.,N.A.
EUGENIUSZ ROGALEWSKI, M.Sc.
MIROSŁAW BESLER
Ship Design and Research Centre, Gdańsk
Ship Structures Division

Comparison of FEM structural analysis and strain gauge measurements of a deck crane

SUMMARY

A new universal 40 t deck crane for bulk carriers was constructed by the Towimor S.A., Toruń, the main Polish supplier of deck cranes and deck machinery [1]. Strain gauge measurements of the crane were performed during the stand tests at the factory.

After the tests a finite element analysis of the crane was carried out to provide additional detail information for checking accuracy of the numerical modelling in view of improving the applied FE model. In this study application of the FE method played a role independent of the experiments. Comparison of the results obtained from the two methods made it possible to improve the FE model and support the experimental results.

INTRODUCTION

Possibilities of the strain gauge measurements are limited by the fact of reading the stresses only in selected points of a structure. Therefore the strain gauge measurements can not replace the global strength analysis carried out by means of the finite element method (FEM) at the stage of structural safety estimation.

The objectives of the present work are as follows :

- Verification of the FE model of the crane boom by comparing the measurement results at the test conditions presented in [2] with results of FEM computations of the boom at some of the test conditions.
- Estimation of credibility of the strain gauge measurements used without carrying out computer structural analysis in advance.
- Estimation of the maximum real stress in the crane boom structure on the basis of the strain gauge measurements.

Errors of using the FEM are mainly due to numerical approximations and structural idealization. Accuracy of the numerical approximations can be verified by examining results of parametric studies or by comparing results from different calculation methods, but physical experiments are usually not required.

The errors due to structural idealization can occur when a real structure is replaced by an idealized model to make the analysis possible. Physical testing, and in particular that of the real structure, is the only way to check the accuracy of a structural idealization.

Although no crane is exactly the same as the considered one, the experience gained from an improved structural idealization is applicable to other structures too.

EXPERIMENTAL INVESTIGATIONS

Strain gauge measurements of the FS40030/32033D5R01 TOWIMOR electro-hydraulic ship-deck crane were made to check stress magnitudes in the crane structure under test load and at the crane support (ship) heel specified by the crane manufacturer. The tests were carried out on a special test stand at the crane factory in compliance with the approved test program. Complete description of the tests can be found in [2]. The strain gauge measurements were performed with the use of the following instruments and materials :

* KWS 3073 Hottinger strain gauge signal amplifier
* DATAGO computer with „Flash-12" Strawberry Tree 16-channel analogue card used for process recording, characterized by the following working parameters :
  - operation mode : Fast Mode
  - number of recorded parameters : 16+1 (inner time)
  - sampling frequency : 50 Hz (Analogue Input and LOG)
  - number of samples per channel : about 4000
  - operation voltage range : ±10V
* 10/120 RY41HBM strain gauge delta rosettes and 10/120 LY 11 HBM single strain gauges.
* Surface preparation materials, glues and strain gauge protecting agents manufactured by the Vishay Measurement Group.

Arrangement of the single strain gauges (P) and rosettes (R) installed on the crane boom is depicted in Fig.1.

Zero - strain value was assumed at the vertical position of the crane boom with its support deflected back by 5°. TheYoung's modulus $E = 2.06 \times 10^5$ MPa and Poisson's ratio $n = 0.285$ were assumed for stress calculation.

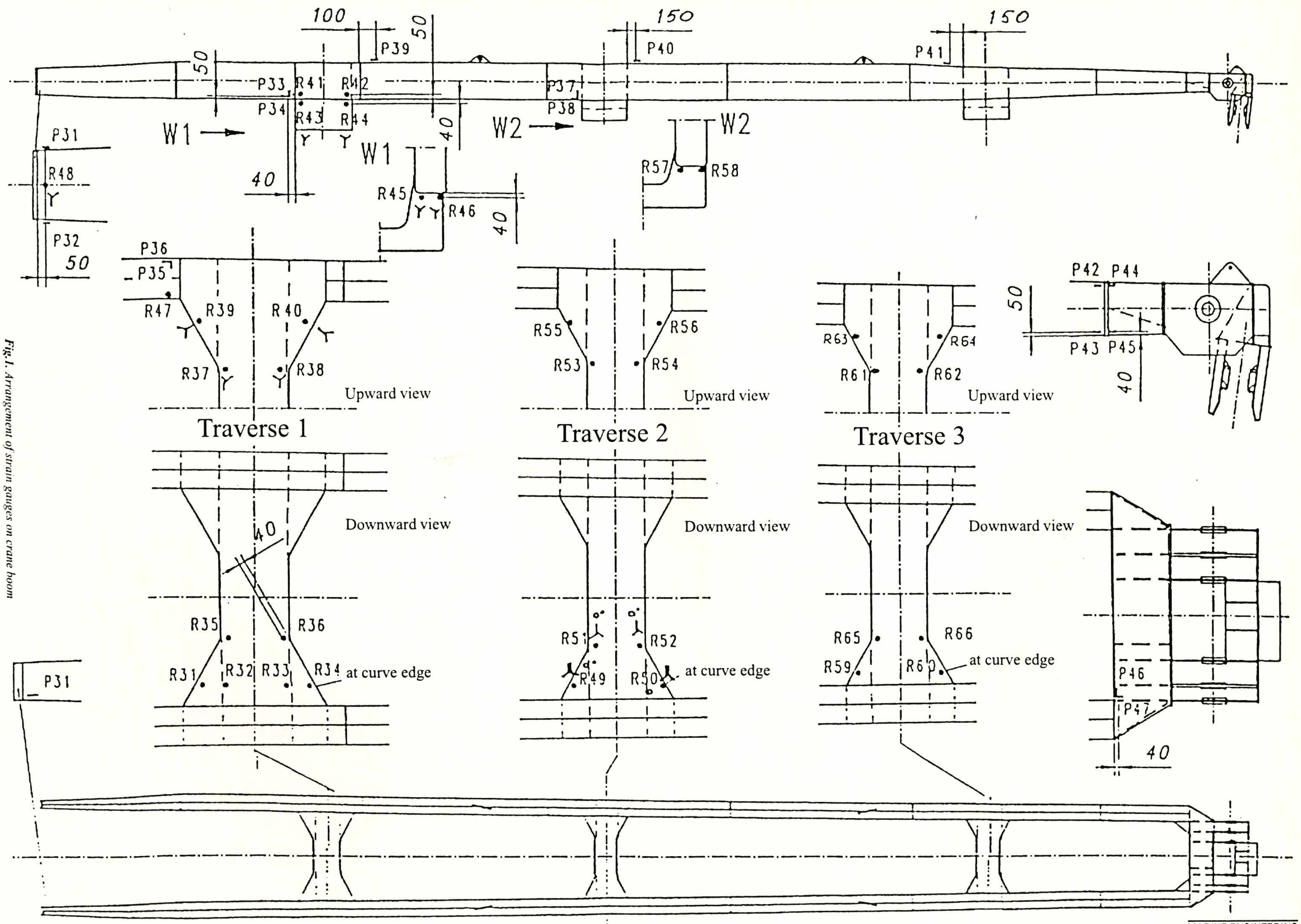

Fig.1. Arrangement of strain gauges on crane boom

METHOD OF COMPARATIVE COMPUTATIONS

Test conditions characterized by the greatest absolute value of stress measured in the crane boom were selected for making comparisons. Test symbols in accordance with [2], and the maximum measured stress values are shown in Tab.1

Tab.1. Selected crane test conditions

Test symbol acc. to [2]	Crane test conditions	Maximum stress [MPa] Gauge symbol
Test 305	Q=40 ton, reach R=30 m, clockwise rotation by 90°, starboard heel by 5° at the moment of start	-142(-115)/P40
Test 009	Q=32 ton, reach R=33 m, clockwise rotation by 90°, starboard heel by 5° at the moment of start	-116/P39

The measurement process during the test 009 and 305 was subdivided into three time intervals (stages) :

Stage I: Lifting the load from the ground up to a specified height, (time interval: t_0 - t_1)
Stage II: Support rotation by 90° with a specified rotational speed, (time interval: t_1 - t_2)
Stage III: Stopping the rotation, the load swings with the fixed period T.

During the test the time-histories of operations given in Tab.1 were recorded. As the number of measuring points on the crane boom in the test 009 was very small, the computational analysis was limited to quasi-static calculations for the test 305 only, carried out for the following situations :

- the test starting time (t_0), just before load lifting, the crane in starting position with the boom under its dead weight only
- static lifting the weight Q=40 t, the time instant (t_5) = (t_0) + 5 s, loading condition „start 5_1"
- swinging the weight Q (to the right) when rotating the crane boom, the time instant (t_{32}) = (t_0) + 32 s, loading condition „start+40_1_right_bp"

The situations could be distinguished on the basis of the recorded stress time-histories presented in Fig. 2, but introducing a secondary interpretation of the stress time-histories from the strain gauge records was necessary since neither start /end points of individual test phases nor swing period (T) and kinematics of motion were recorded in [2]. It could cause systematic errors in defining the loading conditions of the tests.

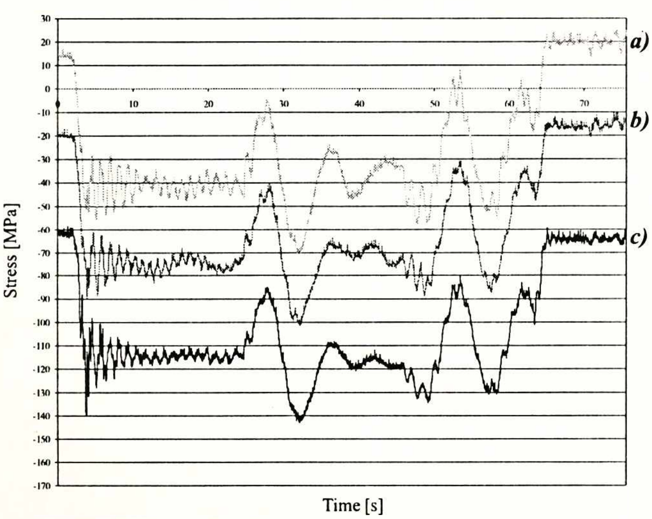

Fig.2. Stress records from test 305, measured by the strain gauges : (a) P32+20, (b) P31 and (c) P40
Test start at t_0= 2s, rotation start at t_1= 24s, rotation end at t_2= 45s , test end at t_3=64s.

After lifting the weight (the time interval t_0 - t_1) the crane support starts uniform rotation with the crane boom head moving along the arc = (π/2 × R), where R - rotation radius.

When the support starts (or stops) rotating, the weight Q suspended on the ropes initiates swinging motion with the period which can be determined from the strain gauge records by assuming the mathematical pendulum law to calculate the period T as follows :

$$T=2\pi\sqrt{\frac{l}{g}}$$

The weight speed (V_0) within the time t_1- t_2 was found from the formula :

$$V_0=\left(\frac{\pi}{2}R\right):(t_1-t_2)$$

The maximum weight deflection angle α at the time instant t_3 in the direction of motion was computed from the weight speed at the moment of support stopping (or starting) :

$$\frac{mV_0^2}{2}=mgh \qquad \frac{l-h}{l}=\cos\alpha$$

where :
l - length of the pendulum
g - acceleration of gravity
h - change of weight height (rise) after stopping
m - mass of test weight
α - maximum deflection angle of the weight.

Input data and calculated values of the maximum deflection angle α are given in Tab.2.

Tab.2. Input data and calculated values of the maximum deflection angle a

Test symbol	Channel number	Swing period T [s]	Pendulum length l [m]	Rotation time [s]	Rotation radius R [m]	Arc length π/2 x R [m]	Weight speed V_0 [m/s]	Weight rise h [m]	cos α	Weight deflection angle α [°]
305	3	8.45	17.77	21.00	30.00	47.10	2.24	0.26	0.986	9.75
009	1	7.09	12.52	24.00	33.00	51.81	2.16	0.24	0.981	11.1

NUMERICAL ANALYSIS

A sketch of the FE model of the crane with applied forces is shown in Fig.3. The calculation model was prepared with the use of MSC PATRAN graphic pre-processor. The model's geometry is based on the technical documentation supplied by the crane manufacturer.

The model covering the crane support and boom structures accounted for :

- Physical properties of the system of span ropes and cargo runners. The ropes were modeled as ROD elements.
- Physical properties of the crane material (St52-3 high strength steel), range of plate thickness (of CQUAD4 quadrilateral elements and CTRIA3 triangular ones), as well as of the boom internal diaphragms and stiffeners (modeled as CBAR beams with 6 degrees of freedom).

The FE model consisted of 16954 finite elements, 14817 nodes and 75392 degrees of freedom. Calculations were performed at the loading conditions of the test 305 specified in Tab.1 and 2.

The system of cargo runners was replaced by the resultant forces applied to the crane boom head in the direction of cargo runners system to remove the influence of cargo runner stiffness on the crane boom distortion due to its dead-weight and test loading. Values of the resultant forces found from a separate analysis amounted to 614 kN. Their directions and points of application are shown in Fig.3.

Tab.3. Computed versus measured principal stresses for test 305 [MPa]

Time instant		Gauge symbol						
		R49	R54	R55	R56	P40	P31	P32
t_0 t = 0 s	Measured	-12	5	-9	15	-62	-20	-6
	Computed	-10.1	4.37	-2.0	1.39	-62.5	-17.2	-5.58
t_5 t = 5 s	Measured	-55	15	-30	34	-132 (-115)	-87	-75
	Computed	-42.5	19	-7	9.90	-110	-68	-51
t_{32} t = 32 s	Measured	-90	24	-45	51	-142	-100	-90
	Computed	-93.5	40	-18.7	25.8	-159	-105	-86

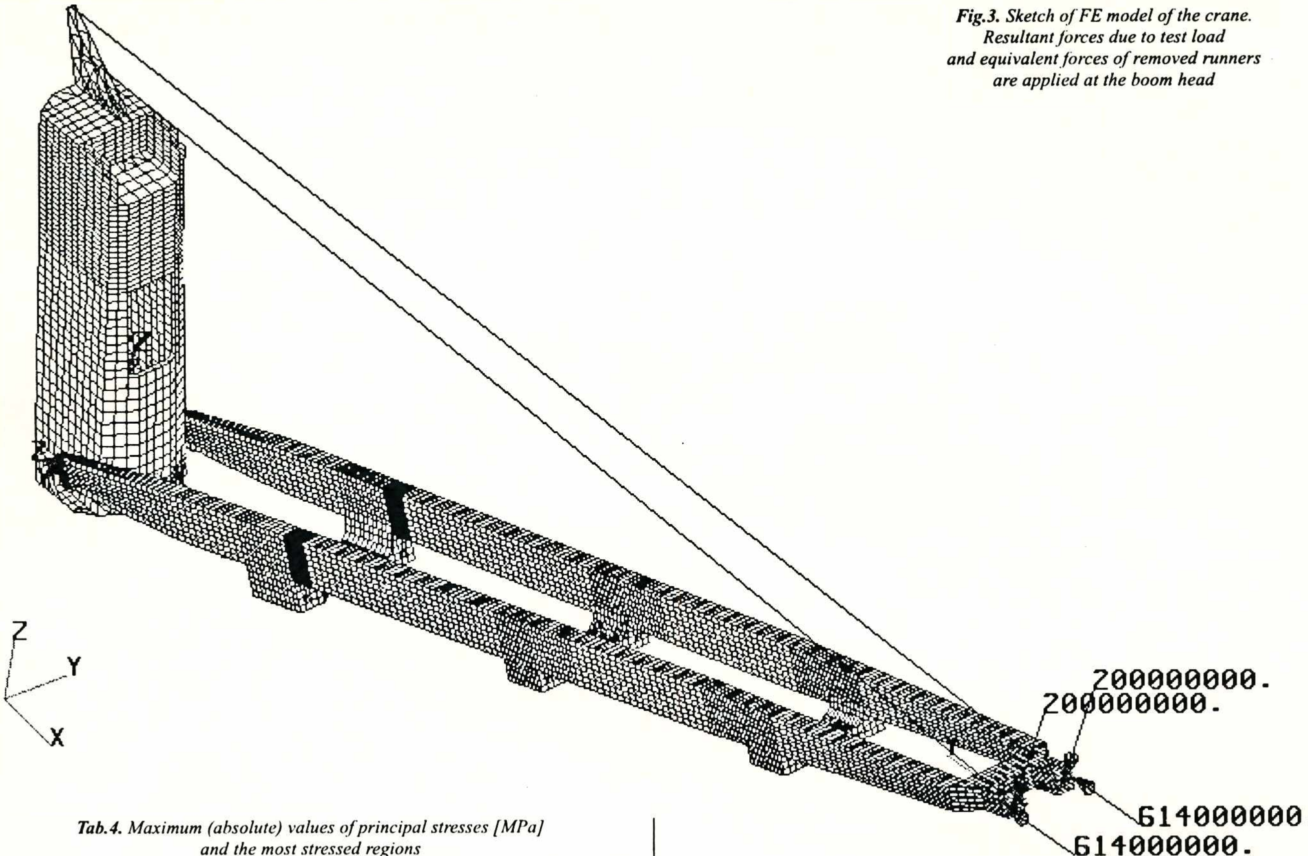

Fig.3. Sketch of FE model of the crane. Resultant forces due to test load and equivalent forces of removed runners are applied at the boom head

Tab.4. Maximum (absolute) values of principal stresses [MPa] and the most stressed regions

Time instant counted from start of test 305	Maximum (out of all channels) measured stress value at a given time /gauge symbol	Location of the most stressed region (as measured)	Maximum computed value of stress	Location of the most stressed region (as computed, see Fig.4 and 5)
t = 5 s	-132(-115)/P40	At right-hand carrying beam fore from traverse No. 2	-127	At right-hand carrying beam fore from traverse No.1
t = 32 s	-142/P40	At right-hand carrying beam fore from traverse No. 2	1)-183 2) 172	1) At right-hand carrying beam fore from traverse No.1 2) At traverse No.1

COMPARISON OF RESULTS OF COMPUTATIONS AND STRAIN GAUGE MEASUREMENTS

Findings from the comparison of the results of the computations and strain gauge measurements (see Tab.3 and 4) are as follows :

⇒ In general the computation results satisfactorily agree with the experimental ones obtained from P40, P31, P32 strain gauges fixed at the crane boom, at all three time instants (i.e. t = 0,5,32 s) provided that the static component of the measured stress is taken for t = 5 s (e.g. the value in brackets in Tab.3). The same conclusion holds for the principal stress of the strain gauge rosettes R49 and R54 placed on the traverse No.2.

⇒ The agreement is generally poor in the case of the strain gauge rosettes R55 and R56 placed on the traverse No.2. The main reason of the discrepancy might be an inadequate idealization of the crane boom support.

⇒ Tab.4 shows the maximum calculated stress values and their location within the crane boom structure versus the maximum stress values measured by the corresponding strain gauges at t =5 s and t = 32 s time instants counted from the test start. The measurements themselves without carrying out a relevant structural analysis in advance do not give the full picture of stress distribution ; neither maximum stress values nor most stressed regions of the structure can be determined.

⇒ The most stressed regions within the crane boom determined from the FE analysis are shown in Fig.4 and 5.

CONCLUSIONS

❖ A reliable structural idealization and, to a smaller extent, its discretization to perform FE analysis is still a very demanding task especially as far as structural optimization is concerned, though reliable structural analysis methods and computer programs are easily available to the designer.

❖ Experimental investigations might be necessary to verify assumed loads and/or boundary conditions. And inversely, routine tests of the prototype do not provide enough information to optimize a designed structure, without preforming an appropriate FE structural analysis in advance.

❖ The following conclusions are offered in result of the comparison of the outputs of the investigations in question :
- lateral bending of the crane boom greatly influences its strength, and the maximum stress in it is strongly dependent on the stiffness of the structural connection of the boom heel to its cast par; it means that the structural behaviour of the crane is better understood now
- the numerical computations and test measurements are mutually supportive
- the errors of the FE modelling of the crane have been identified making it possible to modify a FE model in view of improving accuracy of computations
- the numerical simulation of the crane behaviour provides a guidance for further experimental investigations.

❖ From the presented comparisons it also follows that FE modelling of the ship crane still needs some improvements. The main cause of the poor agreement between FE calculation and experimental results in the case of R55 and R56 strain gauge rosettes could be the assumption of the rigid connection of the crane boom heel to its massive cast part which was modeled by means of solid elements instead of assuming 4 bolts only placed close to the cross-section corners and initially pre-tensioned to prescribed tension values, as it results from an independent analysis of the crane [4].

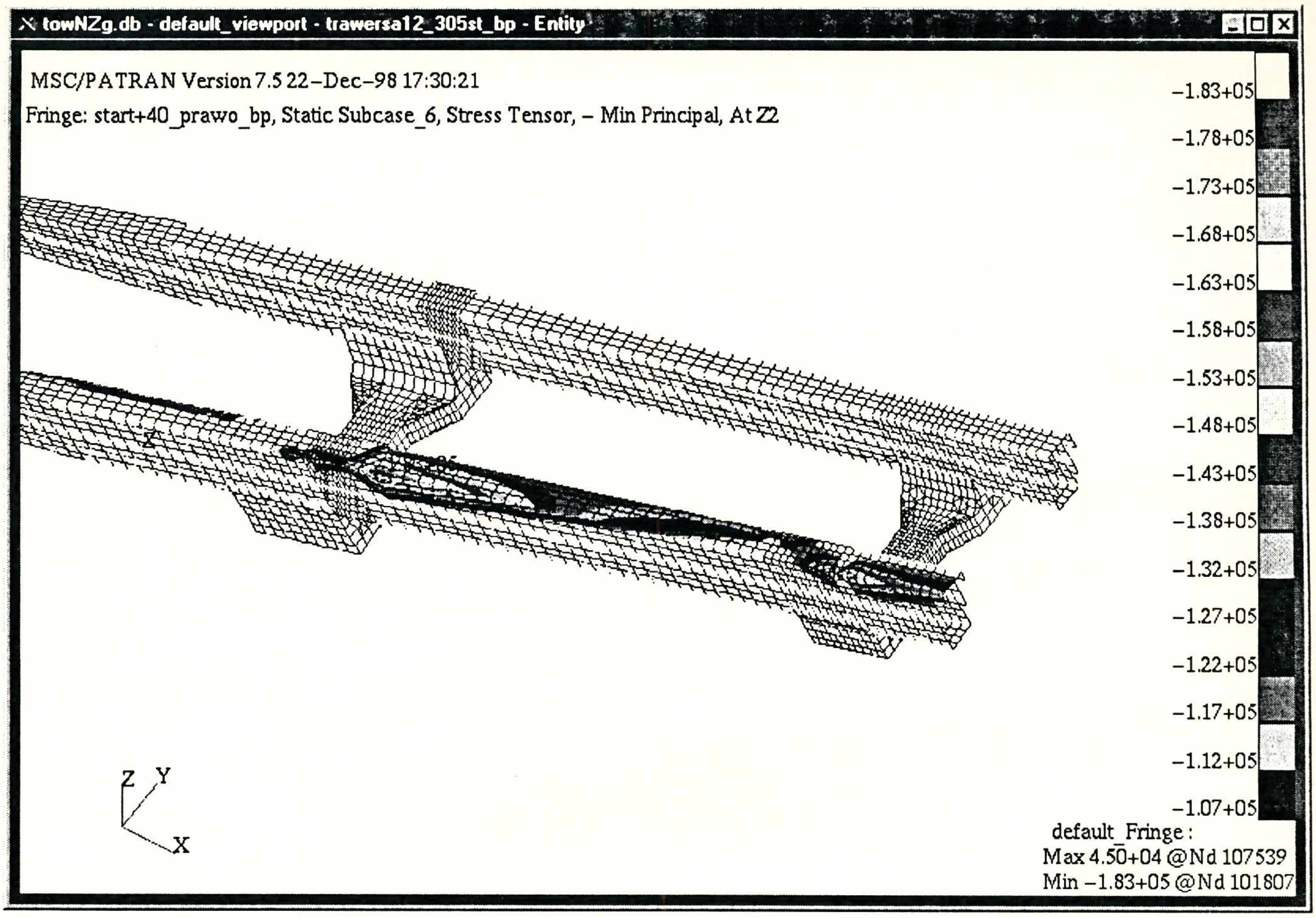

Fig.4. Principal stresses in the region between traverse No.1 and 2 of the crane boom

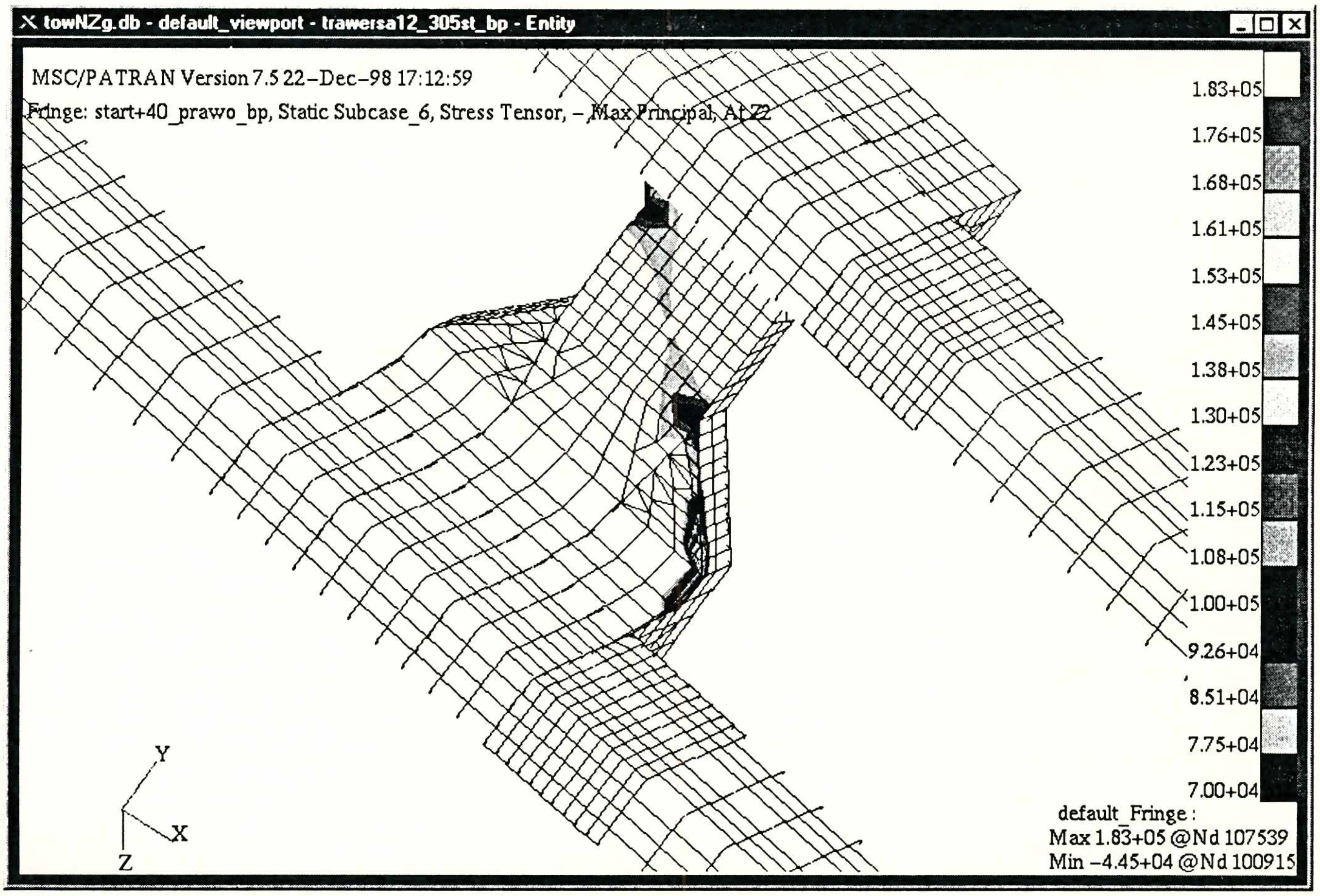

Fig.5. Principal stresses in the heel of the right-hand carrying beam

- Also, the weight loads assumed in the calculation, i.e. their directions and values need direct experimental verification. To obtain a reliable idealization of the crane specially arranged crane tests are necessary. Additional strain gauge measurements should be made simultaneously in the first and second traverses. Also the maximum deflection angle of the weight ropes as well as the displacements of the crane boom top itself should be directly measured. Both 305 and 009 test conditions specified in Tab.1 have to be complied with as a minimum.

BIBLIOGRAPHY

1. Towimor S.A.: „New Universal 35t Crane for Bulk Carriers". Shiff & Hafen 5/96
2. Rogalewski E., Besler M.: „Żuraw typu FS40030/32033D5R01 – Badania tensometryczne konstrukcji w zakresie badań ruchowych pod obciążeniem dynamicznym". Raport Badania nr RK-97/B-119. CTO. Gdańsk, 1997
3. Konieczny L., Litwinienko G., Rogalewski E., Besler M.: „Porównanie wyników analizy strukturalnej MES dźwigu okrętowego z wynikami badań tensometrycznych". Raport Techniczny nr RK-98/T-080. CTO. Gdańsk, 1998
4. Szymczak J.: „Naprężenia eksploatacyjne w konstrukcji żurawia FTS40030/5D4R01". Raport Techniczny nr RK-98/T-105. CTO. Gdańsk, 1998

Appraised by Mieczysław Hann, Assoc.Prof.,D.Sc.,M.E.

Conferences

XX Symposium on ship propulsion plants

In October 1998 the Institute of Construction and Propulsion of Vessels, Polish Naval Academy, Gdynia, organized XX Symposium on Ship Propulsion Plants. The symposia are yearly scientific meetings of representatives of the ship power plant departments or institutes of the technical universities and maritime academies in Gdańsk, Gdynia and Szczecin and of the Polish Naval Academy of Gdynia, devoted to problems of research, design and exploitation of ship propulsion plants and their equipment.

Authors of 23 papers read during the symposium shared their experience and achievements with the Symposium participants. The papers dealt with the following themes :

- Optimization of operation of the waste heat utilization boilers, fuel supply and lubricating systems for diesel engines (4 papers)
- Computer aiding the calculation, simulation, measurement and assessment processes (4 papers)
- Laboratory stands for testing selected ship devices and energy processes (3 papers)
- Assessment of technical state, durability and reliability of power plant devices (3 papers)
- Modelling the power plant installations and operational characteristics of devices (2 papers)
- Identification of technological and operational processes on floating units (2 papers)
- Methods of analyzing the energy processes in diesel engine power plants (2 papers)
- Emission of toxic compounds confronted with marine environment protection (2 papers)
- Development of propulsion systems for fast floating units.

Authors from the Polish Naval Academy, two technical universities and the Maritime University of Szczecin contributed in preparation of the Symposium materials to the greatest extent (5 to 6 papers prepared by each team).

The Symposium was held in 5 sessions with the participantion of, apart from the participants from the above mentioned universities, also representatives of shipyards, shipowners, design offices as well as several maritime economy enterprises and institutions.

Scientific Conference and Workshop on Diving

In December 1998 the yearly, already fifth, Scientific Conference and Workshop on Diving was held in Gdynia. It was organized by Polish scientific centres and military services dealing with medical and technical aspects of diving. Polish Navy, the leader in the field of diving in Poland, hosted the conference.

24 papers were presented to over 100 participants mainly from military circles. The papers were focused on two broad aspects :

„Technical problems of diving"
and
„Medical problems of diving".

A single paper was devoted to each of the themes :

- Nowaday problems of diving in Poland
- Selection and configuration of equipment for technical diving
- Saturated heliox diving in the Baltic Sea
- Development of decompression theory
- Principles of feeding the divers.

The remaining papers (2 to 5 per one theme) were focused on such problems as :

- Diving safety (2 papers)
- Rescue of divers and submarine crews (3 papers)
- Training the divers and frogmen (3 papers)
- Breathing mixtures for diving (2 papers)
- Disease diagnostics and examination of divers (5 papers)
- Ophthalmologic and laryngologic consequences of diving (2 papers)
- Consequences of pressure injury of lungs (2 papers).

Also, the Conference participants had the opportunity of being acquainted with four reports on course and results of visits of Polish experts to foreign diving centres and of taking part in international conferences abroad.

Taking the opportunity, three firms presented their purchase offers of diving equipment and specialty products.

It was also possible to visit the Polish Military Training Centre of Divers and Frogmen, assist at practical training events and be acquainted with the centre's facilities.