Fatigue life of steel laser-welded panels

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ABSTRACT

This paper presents a proposal of algorithm for determining fatigue life of steel laser-welded panels, elaborated on the basis of results of the author's laboratory tests of full-scale structural models. The methodical algorithm and an example of elaborated design curve is presented.

Keywords : laser weld, laboratory test, strength properties, fatigue of structure

INTRODUCTION

The idea of replacement of the classical ship hull structure – developed for centuries – by a novel thin double - shell structure having most of its internal members contained inside it, emerged in the end of the 1950s, however serious interest to it was only paid by US Navy which introduced LASCOR panels as late as in the end of the 1980s. The most spectacular example of this application has been the design of aerial platform for USS „Mt. Whitney", which has made it possible to decrease the weight of the high-placed structure by 9 t. It significantly contributed in improving the ship's stability, Fig.1.

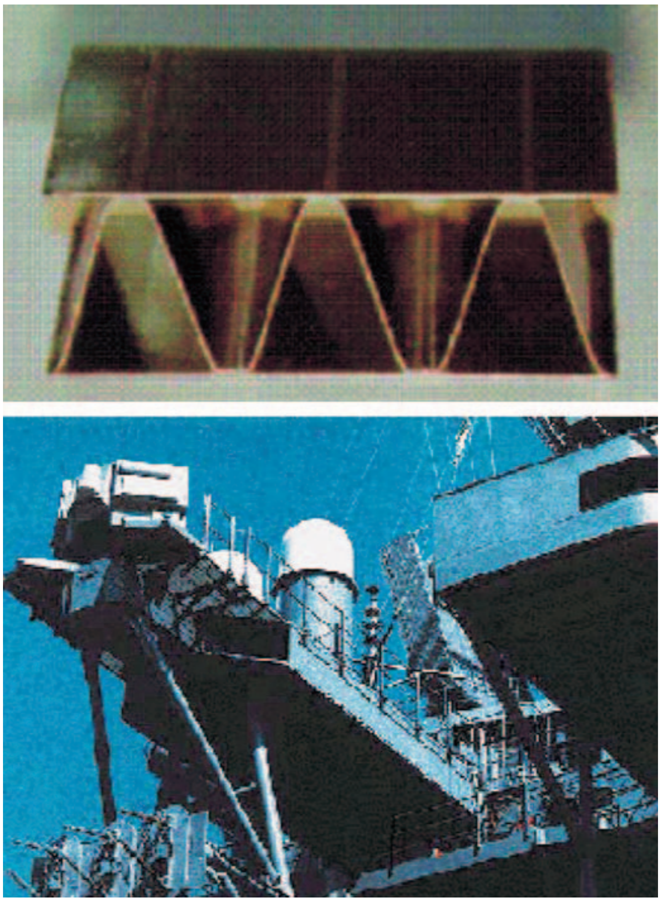

Fig. 1. The aerial platform made of LASCOR panel .

In order to ensure fulfillment of safety conditions for total assumed service time the conditions should be verified with taking into account the criteria associated with structural strength, corrosion protection and fire resistance. For the classical ship steel structure the criteria have been developed for a few dozen of years and they now form a systematically verified set of relevant requirements issued by ship classification societies. Their guidelines and recommendations dealing with the assessment of fatigue life of hull structures are one of the latest and still developed groups of the requirements of the kind.

THE AUTHOR'S RESEARCH ON FATIGUE QUALITIES OF SANDWICH MODELS

In contrast to the classical welded steel structures the problems – especially those dealing with strength – associated with the application of novel solutions such as steel double-shell complex sandwich structures, have been investigated so far to an insufficient extent. In particular the fatigue strength problems of such structures have started to be recognized and investigated as late as in the last years. Whereas every application of novel solutions of ship hull strength structure requires to have at one's disposal relevant analytical procedures including those concerning fatigue life assessment. Such procedures for steel sandwich panels are still lacking.

The algorithms successfully used in shipbuilding, elaborated for classical structures, have not been so far positively verified to be used in sandwich structures because of their different features and lack of research data.

Hence an attempt has been made to elaborate a procedure for estimation of fatigue life of such structures within the frame of the research programs financially supported by European Union, in which the Faculty of Ocean Engineering and Ship Technology, Gdańsk University of Technology, has taken part. In the frame of the research program, behaviour of steel sandwich structures in various versions of geometry, boundary conditions and load configuration, were tested under variable load.

Tests of the models having 3000x1500 mm overall dimensions, („a" type)

The fatigue tests were performed under concentrated load applied in the centre of the model rigidly restrained at all its edges. The test stand and the model itself is shown in Fig.2.

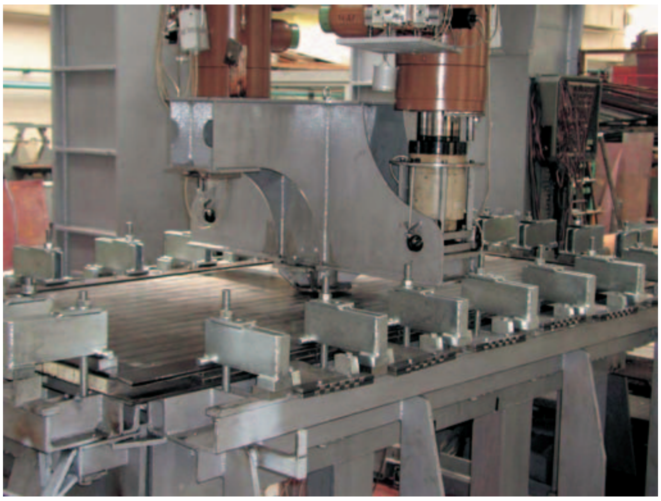

Fig.2. *The model „**a**" under fatigue testing .*

In the fatigue tests in question load levels were selected on the basis of their calibration with the use of successive static load tests during which signals from strain gauges placed on both shell plates, were recorded.

When tested, the models were loaded by cyclic constant--amplitude load of about 4 Hz frequency and the stress ratio R equal to about 0.1.

Fatigue cracks appeared in the transition zone between the face of weld and original material of the shell plate under tension. The cracks always appeared just under the middle web. However in two cases the cracks of a similar character appeared also under third web, counting from the mid-span of the model. In all the cases the cracks were caused by the tensile stresses in the shell plate, acting perpendicularly to the course of the weld. In Fig.3 is shown the crack occurrence area and in Fig.4 – – a fractographic image of the crack surface.

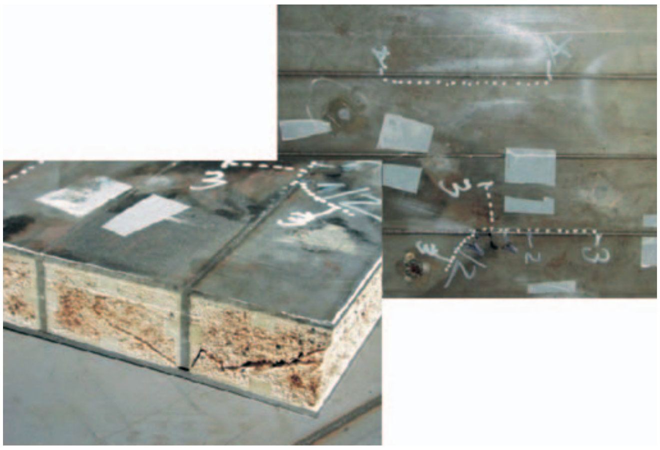

Fig. 3. *Fatigue cracks in the model .*

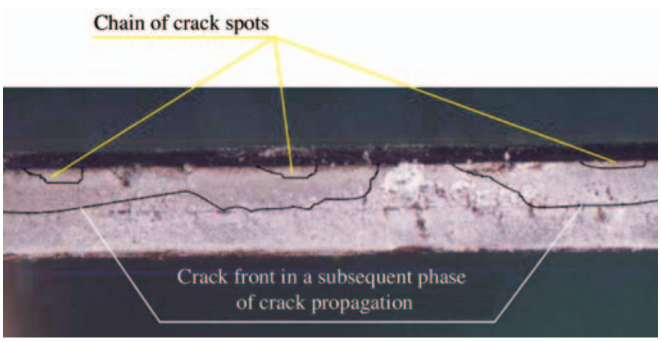

Fig. 4. *Fatigue crack surface .*

A macro-fractographic analysis revealed the presence of a chain of tiny fatigue spots on the crack surface. This confirms that the material structure within the crack zone uniform and there is no clearly weak points of the kind of welding defect.

Tests of the models having 1000x500 mm overall dimensions, („b" type)

The models having the same cross-sectional geometry as in the preceding case, were loaded by a concentrated cyclic load applied in the mid-span of the model freely supported along its longer sides.

In the tested models the failure process – regardless of a level of applied load – progressed in the same way : fatigue crack was initiated in the laser weld joining the extreme web with the shell plating in the vicinity of the web's end and it next propagated along the web towards the model centre, Fig.5.

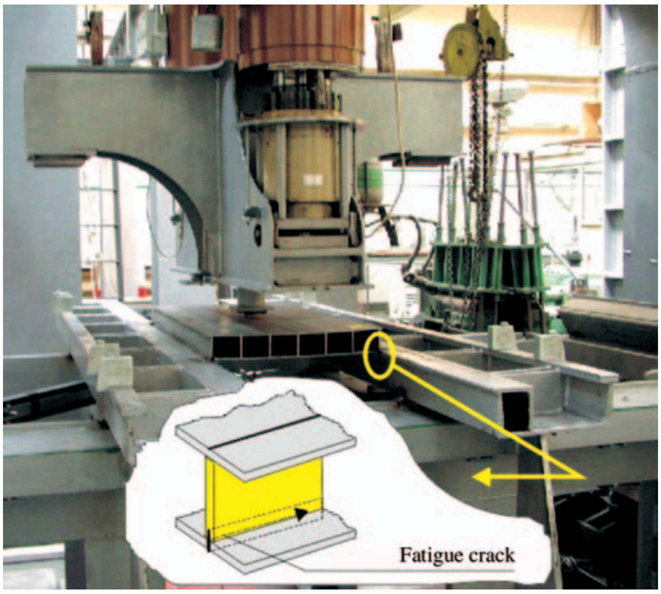

Fig. 5. *The way of progressing the failure process in the tested „**b**" models .*

Tests of models of joints

Some solutions of the joints were also tested, the same as for the models of the geometry close to that of 3000 x 15000 mm models. During the tests, in the sandwich structure on its shell plating surface appeared the cracks initiated in the laser weld and propagating perpendicularly to the course of the weld, Fig.6.

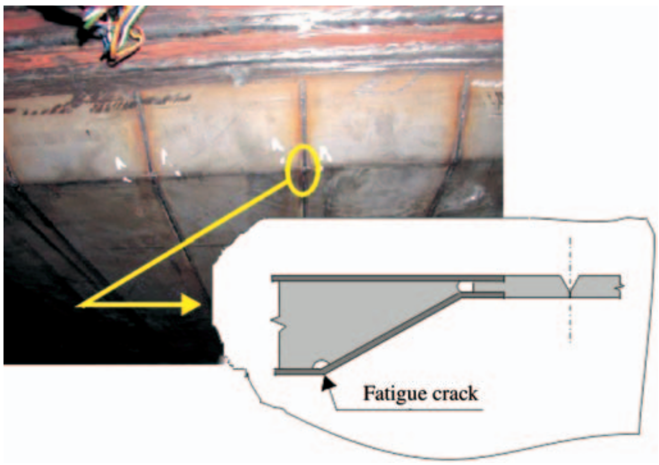

Fig. 6. *Crack in the model under testing .*

A PROPOSAL OF THE PROCEDURE FOR FATIGUE LIFE CALCULATION OF STEEL LASER-WELDED PANELS

Taking also into consideration results of other investigations of this author [1,2,3] one can state in a more general way that in the laser –welded double-shell panels of the webs perpendicularly placed to the shell, one out of the following five cracking models can occur, depending on a type of structure geometry, applied loading and supporting mode, see Fig.7. :

- ⋆ 1st – a crack appearing in the tensioned shell plating in the zone of laser weld penetration, pointing the direction perpendicular to the weld axis, caused by tensile stresses resulting from global bending of the panel
- ⋆ 2nd – a crack appearing in the tensioned shell plating in the laser weld, and next in the shell plate material, pointing the direction perpendicular to the weld axis, caused by tensile stresses resulting from global bending of the panel
- ⋆ 3rd – a crack appearing in the tensioned shell plating, caused by local tensile and shear stresses (such a state should not appear in a properly designed structure)
- ⋆ 4th – a crack appearing in the laser weld in the region where shell plating and end surface of adhering web contact to each other, caused by the weld bending resulting from mutual rotation of the web and adhering strip of shell plating
- ⋆ 5th – a crack appearing in the laser weld in the region where shell plating and end surface of adhering web contact to each other, caused by combined stresses resulting from weld bending and shearing.

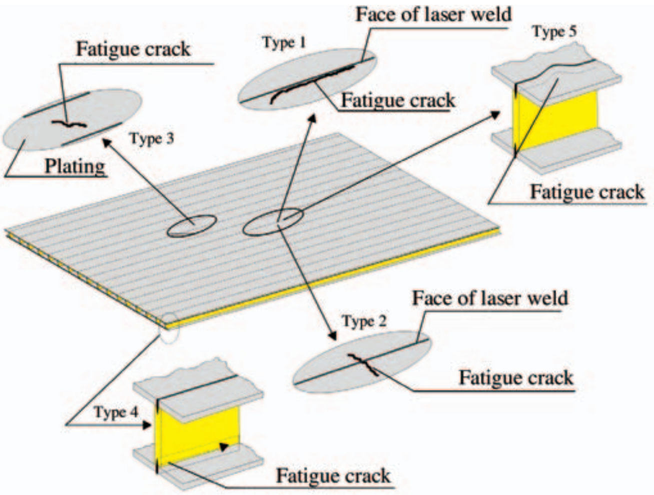

Fig. 7. *Cracking models which can appear in steel sandwich structures .*

For the classical welded steel structures have been proposed several calculation approaches based either on the concept of nominal stresses,"hot spot" method or deformation criteria, Fig.8 [6].

For ship structures they are expressed in the form of guidelines, rules and recommendations issued by ship classification societies.

In Fig.9 the interpretation of the nominal, structural (geometrical) and in-the-notch stresses acting in the weld penetration zone, is presented [5].

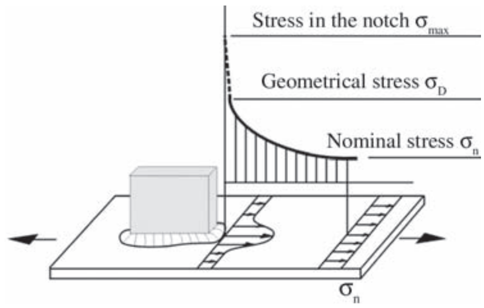

Fig.9. *Interpretation of the nominal, structural (geometrical) and in-the-notch stresses acting in the weld penetration zone [5] .*

The collected results of the investigations make it possible to elaborate procedures for the fatigue life assessment – based on the concept of nominal stresses [4,5] – of the steel laser--welded double-shell panels having their webs perpendicularly placed to shell plating. Such assumption is justified by the fact that the geometry of laser-weld neighbourhood – regardless of full-scale panel dimensions – is always the same. The panels – due to their configuration and internal connections – are obviously much more sensitive to large stresses caused by specific structural features or local manufacturing factors. It could be for instance local deformations of shell plating due to assembling, incorrect transporting or turning in the course of manufacturing process. Initial deformations resulting from laser welds laid non-symmetrically relative to web axis in the course of manufacturing process, constitute a separate problem. Such stress concentrations are random non-predictable phenomena hence during calculation process modelling their influence is not possible. Their influence on fatigue life can be controlled by selecting appropriate manufacturing tolerances and carrying out calculations for the structures initially deformed but still complying with the permissible tolerance limits.

Hence the procedure for fatigue life calculation of steel laser--welded sandwich panel should comprise the following steps :

- ❖ Determination of the field of deformations and stresses
- ❖ Determination of a phenomenon controlling crack development (stress, deformation)
- ❖ Choice of a cracking mechanism (model) and crack occurrence region
- ❖ Determination of a value of the reference parameter for a given cracking model

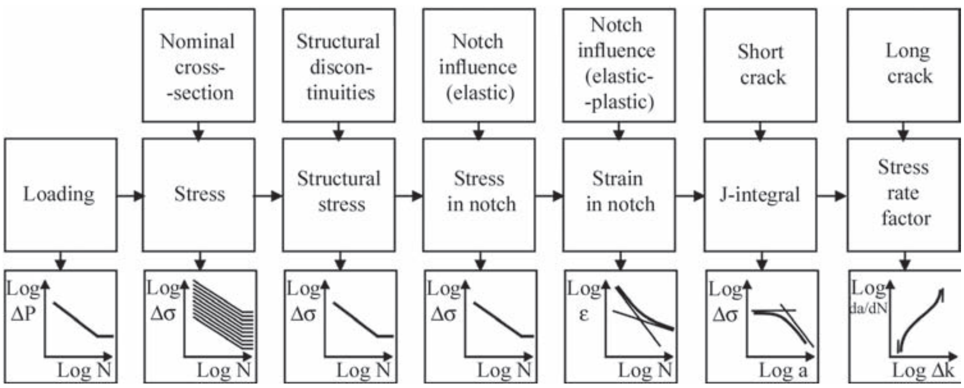

Fig. 8. *Some approaches to fatigue strength calculation [6] .*

- ❖ Choice of an appropriate design curve
- ❖ Determination of fatigue life from the chosen design curve.

In order to conduct calculations in compliance with the above proposed approach it is necessary to have at one's disposal a set of design curves for each of the distinguished cracking models shown in Fig.7. The case „4" creates a problem as it seems that for this cracking model crack development is controlled more by deformation mechanism than stress one. For the remaining cases an important factor conditioning the correctness of obtained results is to assume the same reference stresses for the tests from which design curves are determined and for the calculations when the use is made of the curves – as far as both the choice of a stress tensor component and a way of its calculation is concerned.

The design curves as such can be determined on the basis of laboratory tests of elementary models of joints, and the above mentioned uncertainties can be taken into account by assuming an appropriate value of safety factor.

DESIGN CURVES OF BASIC FATIGUE CRACKING MODELS FOR STEEL LASER-WELDED STRUCTURES

The above postulated necessity of having at one's disposal a set of fatigue design curves for each of the cracking models, based on systematic tests of elementary specimens – which have not been published so far – has constituted a premise to undertake such effort on the basis of own research. In this frame were conducted systematic tests of elementary specimens of a laser-welded joint having its geometry and loading conditions corresponding with the case „1" from Fig.7. Such specimen is shown in Fig.10.

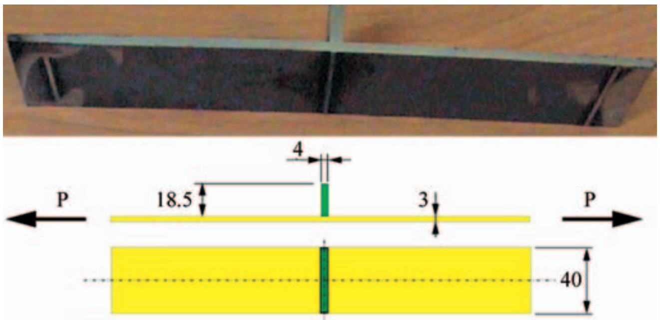

Fig. 10. *Geometry of the specimens used for modelling the case „1" (Fig.7) .*

On the basis of the obtained test results was elaborated a design curve of the slope equivalent to the mean value derived from the results by using the least-squares (RMS) method, and shifted by the value of (–2σ) towards shorter fatigue lives. Such solution guarantees that the fatigue life values calculated on its basis will be achieved with 97.5% probability. The proposed design curve is shown in Fig.11.

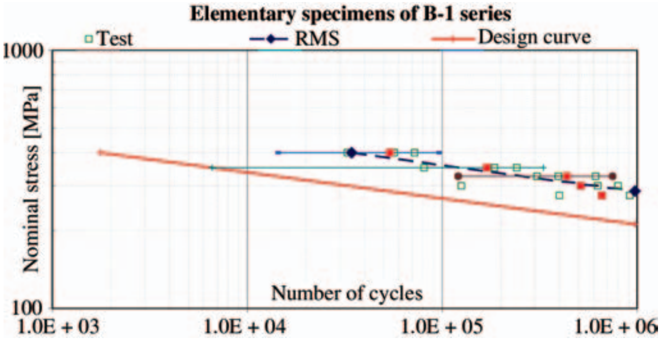

Fig. 11. *The proposed design curve for the 1st cracking model .*

CONCLUSIONS

- ❍ Steel double-shell laser-welded sandwich panels may constitute an alternative solution for ship hull structures as it offers significant weight and space savings as compared with the classical structures.
- ❍ Strength properties of sandwich panels considerably differ from those of ship single-shell structures because of anisotropy of stiffness resulting from their geometrical features, as well as specific properties of laser weld.
- ❍ The different properties make possible application of the algorithms for the assessment of fatigue life prepared for single-shell structures, directly to sandwich structures, doubtful.
- ❍ On the basis of the full-scale model tests of sandwich panels, performed by the author, the cracking models of such structures subjected to variable loads, were revealed and collected.
- ❍ An approach based on nominal stresses was proposed to fatigue life analysis of sandwich panels.
- ❍ For the above mentioned approach a design curve based on the test results of an elementary laser-weld joint, was proposed.

The presented results were derived from the work conducted in the frame of the following research projects financially supported by European Union :

- ❖ „SANDWICH" – **Advanced Composite Sandwich Steel Structures** –5th EU Outline Program, Contract No. G3RD-CT-2000-00256, 2000-2003
- ❖ "SAND.CORe" – **Coordination Action on Advanced Sandwich Structures in the Transportation Industry**, 6th EU Outline Program, Contract No. TCA3-CT-2004-506330 SAND.CORe, 2004-2005
- ❖ „ASPIS" – **Application of Steel Sandwich Panels into Ship Structural Design**, EU research project within the frame of Eureka E!3074 Network, 2003-2006.

NOMENCLATURE

a	– fatigue crack length
K , ΔK	– stress intensity ratio and its range
N	– number of cycles of fatigue load
P , ΔP	– load and load range
R	– load asymmetry ratio
RMS	– root mean square
ε	– unit strain
σ , Δσ	– stress and stress range
σ_n , σ_D , σ_{max}	– nominal, geometrical and notch stresses

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