Research on deformations of laser-welded joint of a steel sandwich structure model

Dariusz Boroński
Academy of Agriculture & Engineering, Bydgoszcz
Janusz Kozak
Gdańsk University of Technology

ABSTRACT

Problems of the behaviour of all-steel, laser welded sandwich panels in plate-to-web contact zone are presented. Results of laboratory tests on determination of deformation field around laser weld under bending load – obtained by laser interferometry technique – are shown. Analysis of strain field distribution is included and some conclusions related to modeling of behaviour of such connection are drawn.

Key words : laser welding, laboratory tests of structural elements, laser interferometry

INTRODUCTION

Developments in novel joining techniques including laser, hybrid (laser – MAG) and friction stir welding have brought about their broader and broader industrial applications, as well as they opened new possibilities for designers to create structures not feasible so far.

Higher accuracy of so made welds and their more uniform quality, increased speed of welding, reduced amount of heat introduced to weld zone, possible automation and use of robots for welding processes – these are some advantages deciding upon fast application of such techniques in space, aircraft, car or shipbuilding industries [1, 2, 3, 4, 5, 6].

Their special position in the case of the application e.g. in shipbuilding [7] or aircraft industry is associated with, a.o., the possibility of building the sandwich structures which consist of load-carrying shell platings stiffened by cores of various forms, that leads, a.o., to a significant reduction of mass of designed objects. However application of the novel solutions usually demands some changes to be introduced to the traditional methods of construction of such objects as aircrafts and ships.

One of the example solutions based on the laser welding technique is a steel double-skin structure stiffened by internal webs joined with the shell platings by using laser welding applied from outside of the object under construction.

The idea of the replacement of the traditional single-skin ship hull structure with a new thin double-skin structure whose system of basic stiffening members is installed in the space between the shell platings, was born in the 1950s, and then it was studied by NASA [8, 9, 10]; however its practical application was attempted by US Navy at the end of the 1980s [11]. Presently Meyer Werft, Germany, applied the solution to the structural panels which appeared ten times stiffer and weighing less by 35% than their conventional equivalents [12].

Such panels have been produced and applied on an industrial scale e.g. to decks of Danube navigation passenger ships built in series by a German shipyard, as well as to bulkhead structures of another passenger ship [13].

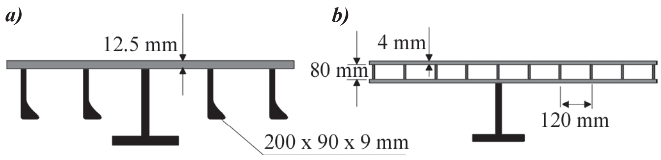


Fig.1. Comparison of a classical deck structure (a) of a ro-ro ship and that built of Meyer's laser-welded panels (b)

However in order to apply the novel structural elements on a large scale – especially to important elements of ship hull structure – it is necessary to have at one's disposal information about their corrosion and fire resistance, and first of all about their technological and strength properties required to obtain approval of ship classification institutions.

The problems have become the theme of the „Sandwich" research program being realized in the scope of 5th Frame Program financially supported by European Commission. Within the research program a team of the Faculty of Ocean Engineering and Ship Technology, Gdańsk University of Technology, carried out verification of strength properties of full-scale double-skin panels internally stiffened by real stiffening member systems and different types of fillers [14]. Some new research problems which have resulted from the above mentioned work, are presently continued in the frame of the ASPIS project realized by the Faculty within EUREKA E!3074 program.

The steel double-skin panels differ from their classical single-skin counterparts by their shear stiffness in the direction of the stiffeners (webs), much greater than that in the direction perpendicular to them, i.e. Dqx>>Dqy. Simultaneously the stiffness is much smaller than that of the relevant classical structure. It means that apart from the collapse mechanisms which may occur in one of the stiffened platings, similar to those possible to occur in the traditional single-skin structures, other mechanisms resulting from mutual interaction of both platings may additionally occur, e.g. a kind of „rotation" of the elements relative to each other around the laser weld as a „hinge" (Fig.2).

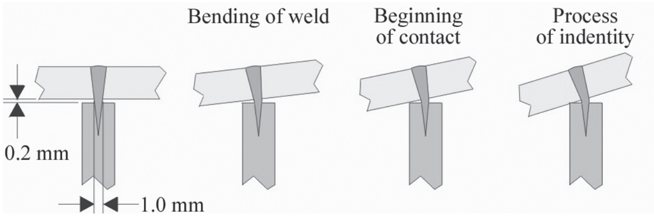


Fig. 2. *Behaviour of laser-welded joint under transverse load*

The phenomenon may be very important for the modelling of behaviour of a structure by means of the finite element method (FEM). By neglecting it an excessively high stiffness characteristics of a modeled structure against that real, may be erroneously calculated. Therefore from the point of view of modelling the behaviour of the entire panel under load it is important to know the macro-scale response of the joint.

The laser-welded joint much differs from a conventional arc-welded joint. As a result of the laser welding a narrow weld surrounded by a small heat-affected zone but with entirely different material properties against those of native material, is obtained.

No universal guidelines (including fatigue test data) have been so far available for fatigue assessment of laser welds, as this is the case for the traditionally made welds [15]. The available results of high-cycle fatigue tests of unnotched specimens containing laser weld [16] indicate that their fatigue strength does not much differ from that of the native material, which can partially result from the better quality (lack of defects) of the weld itself. The result can be also explained on the basis of the local strain approach to fatigue strength in the elastic range. However in the case of the load causing exceedance of the material yield point in the joint, strain values in particular weld zones will be different. It should be also taken into account that plastic strains may occurr not only due to large external loads but also as a result of a complex geometry of the joint leading to strain/stress concentration. Obviously all the above mentioned effects may occur in the considered steel sandwich panels.

In the reported work, being a part of the broader research program, the results of the first task of the research on local strain distribution in weld zone, due to the in-plane loading applied to the shell platings of the sandwich model structure, are presented. In the next phase of the investigations it is intended to analyze strains developed in weld zone during fatigue tests.

OBJECT AND METHOD OF THE RESEARCH

The research program was aimed at revealing the local phenomena in the laser-welded joint under bending in order to collect information necessary for modelling the joint's behaviour. The object (specimen) used in the research represented a fragment of a steel sandwich panel. In Fig.3 its structural arrangement and basic dimensions are shown. In its measurement part the specimen contained three webs joined with both shell platings. The investigations were focused on the joint connecting the middle web with one of the shell platings. The specimens were made of hull structural steel of known mechanical properties.

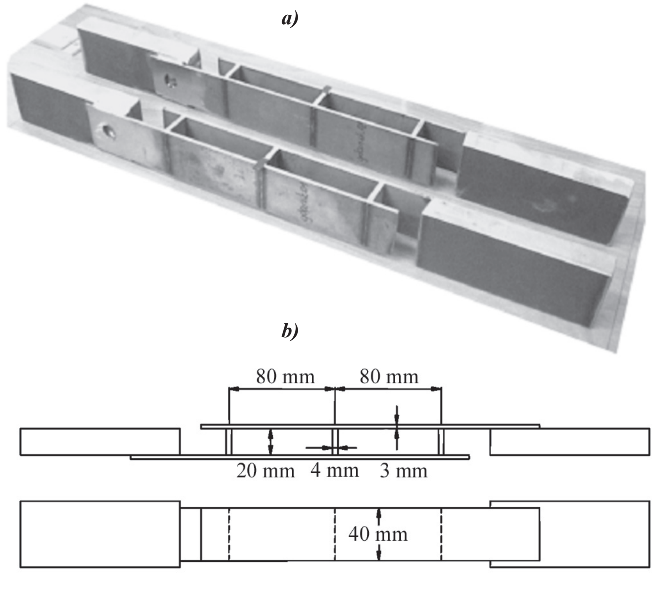


Fig. 3. *The structural arrangement* ***(a)*** *and the main dimensions* ***(b)*** *of the specimens*

The laser grating interferometry technique [17, 18] applied in the automated laser grating extensometer LES [19, 20], was used to investigate strains in the joint and to account for local character of the phenomena occurring in a small area of the joint.

The technique is an optical full-field method based on the phenomenon of interference of two mutually coherent light beams projected on a measurement grating, which produce a pattern of interference lines (fringes) carrying information on relative displacements of the surface of a tested object. Sensitivity of the method depends on an applied laser wave-length and diffraction grating density. In the case of the LES it amounts to 0.42 μm per one interference line. Further analysis of the lines makes it possible to obtain the measurement sensitivity of the order of 20 nm.

The used research instrumentation consisted of the LES extensometer, a fatigue testing machine and PC- class computer together with its accompanying equipment, is shown in Fig. 4.

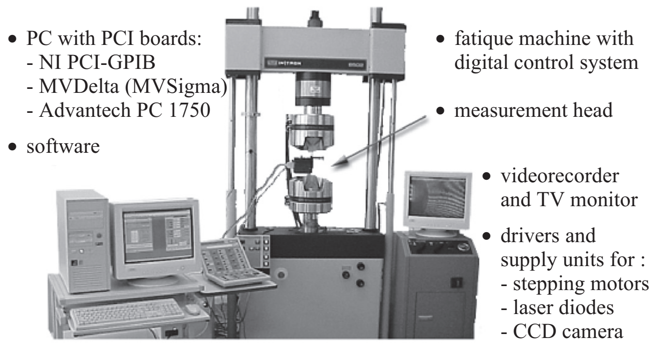


Fig. 4. *Configuration of the used research instrumentation*

Necessary calibration of the optical system can be remotely performed within the LES head. The pattern of interference lines (fringes) obtained during testing can be saved – through the electronic-optical vision system – in the computer memory. The pattern is partially analyzed in the real-time mode, which makes it possible to measure strains in a selected segment of measurement field, and the full information is saved on magnetic disk for further off-line analysis. Setting and operation of the entire research instrumentation can be controlled by means of a special software.

The using of the laser interferometry method demands application of gratings placed onto the specimen's surface. In the investigations in question the gratings of the density of 1200 lines/mm obtained by dusting aluminium onto a matrix prepared on 2' x 2' glass plate, were used. During the preparation of the specimens for testing the 8 mm x 8 mm fragments of the grating were put on the cleaned surface of the joint by glueing the dusted aluminium layer, and then separating it from the matrix after setting the resin.

TEST RESULTS AND THEIR ANALYSIS

During the performed tests the distributions of relative displacements and strains in two mutually perpendicular directions U and V for 16 selected levels of static load (complying with Fig.6 and 8), were determined for values of the loading being under control. The tested specimen fitted with the LES head is shown in Fig.5. The specimens were loaded in accordance with the loading scheme shown in Fig.6.

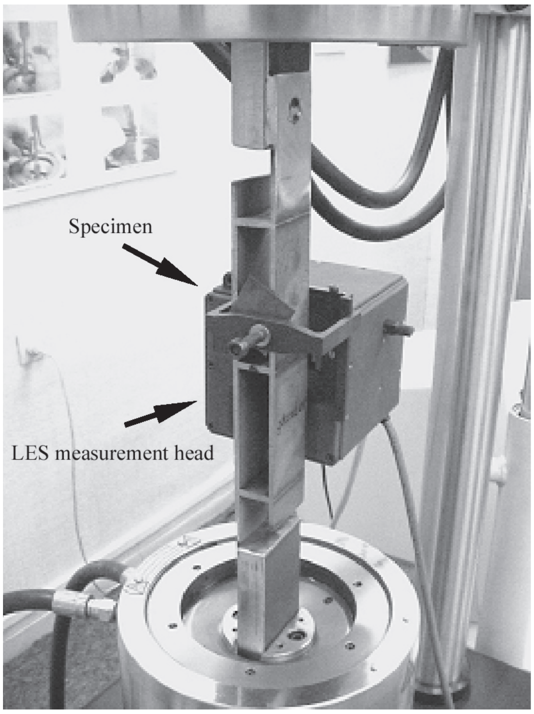
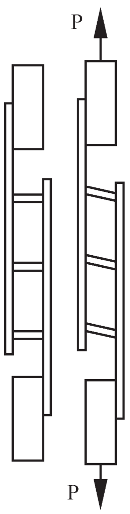


Fig. 5. The sandwich structure model (specimen) under testing



Loading levels

No	Load P [kN]
1.	0.00
2.	0.23
3.	0.55
4.	0.78
5.	0.98
6.	1.25
7.	1.54
8.	2.03
9.	2.28
10.	2.55
11.	2.77
12.	3.04
13.	3.27
14.	3.50
15.	3.82
16.	4.02
17.	0.00

Fig. 6. Loading scheme of the specimen

At particular values of the loading force P the fringe patterns in two analyzed directions U and V were recorded. The measurements were carried out for the middle joint only. The strain measurement field is shown in Fig.7.

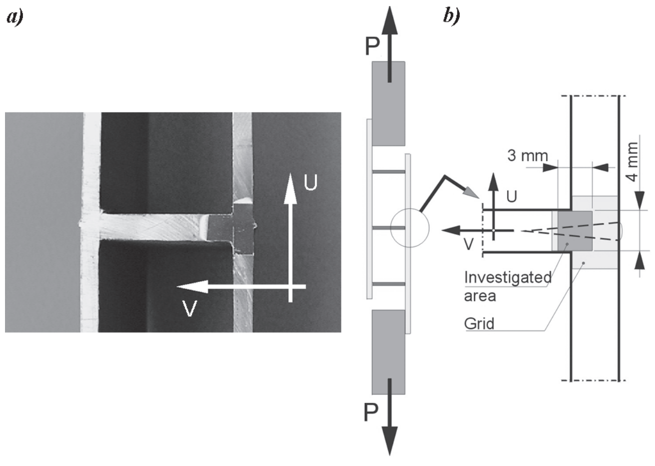


Fig. 7. The specimen with the glued laser grating (a), and the measurement field location relative to the laser weld (b)

The diagram of the load applied to a specimen in function of its elongation, together with the marked points of strain measurement, is presented in Fig.8. In the diagram the permanent elongation which remained in the specimen after unloading, is additionally indicated.

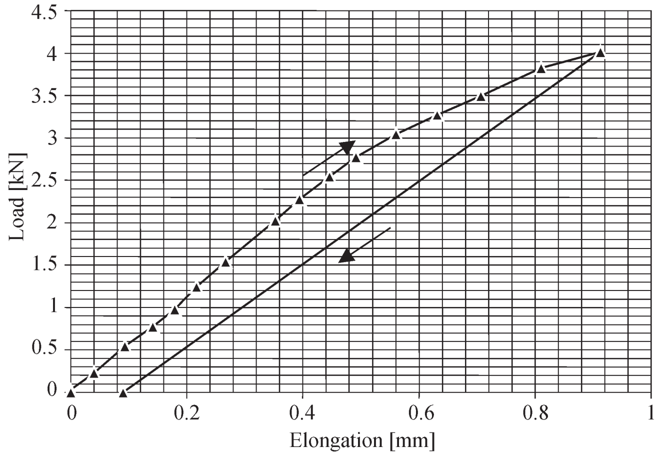


Fig.8. The diagram of the load applied to a specimen in function of its elongation

The example fringe patterns recorded during the tests are shown in Fig.9.

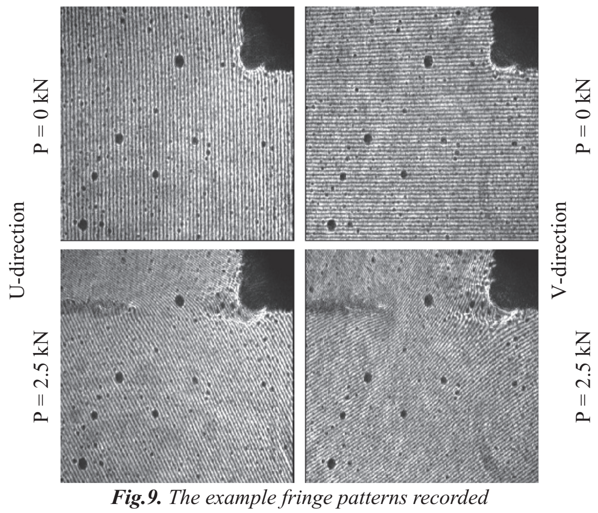


Fig.9. The example fringe patterns recorded at P = 0 kN, and at P = 2.5 kN

The strain analysis was generally limited to the values of the force P = 2.5 kN as large strain values occurred in the contact zone of the web and shell plate, which exceeded the basic measuring range of the applied method (for the mode of automatic measuring and data recording), as well as due to the concentration of fringes resulting from rotation of the specimen's elements under loading.

The obtained fringe patterns were analyzed with the use of numerical procedures making it possible to identify particular fringes and their phases within an analyzed field.

In Fig.10 and 11 are presented the strain distributions determined in the directions V and U, respectively, for successive values of the external force P.

The largest values of tensile strains (along V- axis) in the analyzed area occurred at the edge of the weld, and those of compressive strains – in the web-to-plate contact zone (Fig.12).

Along with increasing the load the increasing strain values occurred both in the compression and tension zones, also a gradual expansion of the zones into the plate material was observed.

The combined influence of the web bending and the web--to-plate contact on the strain distribution in the minimum cross--section of the weld, is shown in Fig.13.

From the analysis of the presented strain distribution it results that the neutral axis of bending, located close to the middle

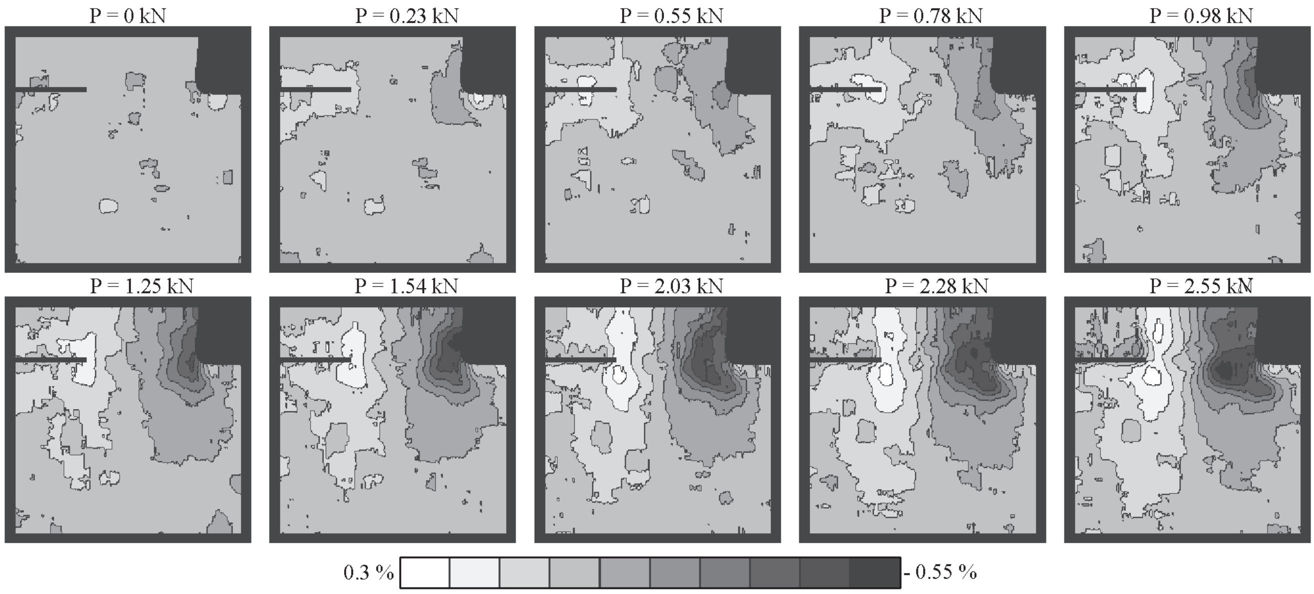


Fig.10. *Strain distributions in V-direction*

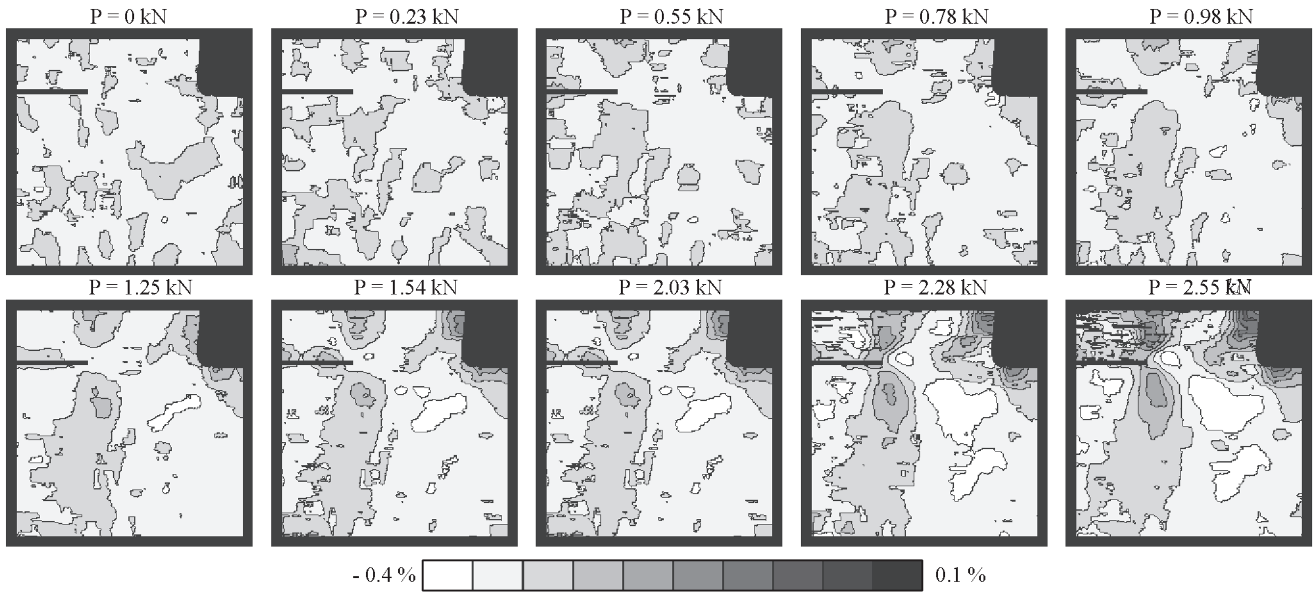


Fig.11. *Strain distributions in U-direction*

From the analysis of the obtained strain distributions along V-axis it can be observed that the axial load applied to the specimen in accordance with the loading scheme (Fig.8), generated a strain gradient typical for bending, in the surroundings of the weld joining the web with the shell plate.Simultaneously the edge of the web exerted contact pressure on the shell plate, that produced the compressive strain zones appearing both in the web and shell plate in the vicinity of the web's edge. (Fig.12).

of the weld, did not change its location despite the web came in contact with the plate during loading the specimen. As a result, only a deviation from linear distribution in the compressive strain zone of the weld occurred. Simultaneuously the contact pressure of the web on the shell plate caused large plastic strains in the contact zone, which exceeded the strains in the weld itself. Hence, such development of strains may indirectly indicate that the yield points of the weld, heat affected zone and native material could significantly differ from each other.

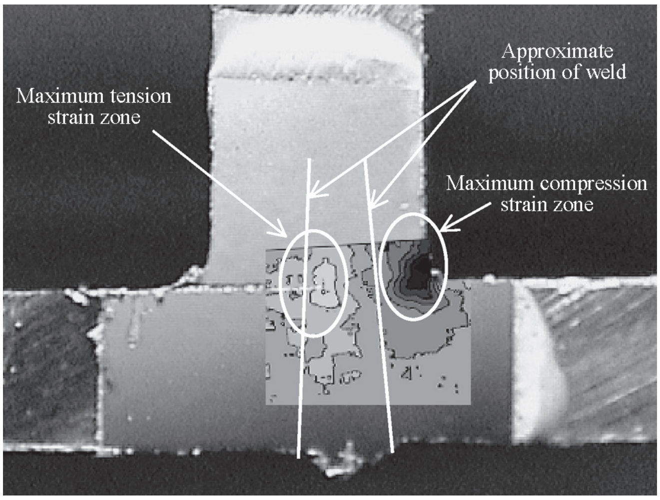


Fig.12. Strain distribution in the weld zone at P = 1.54 kN

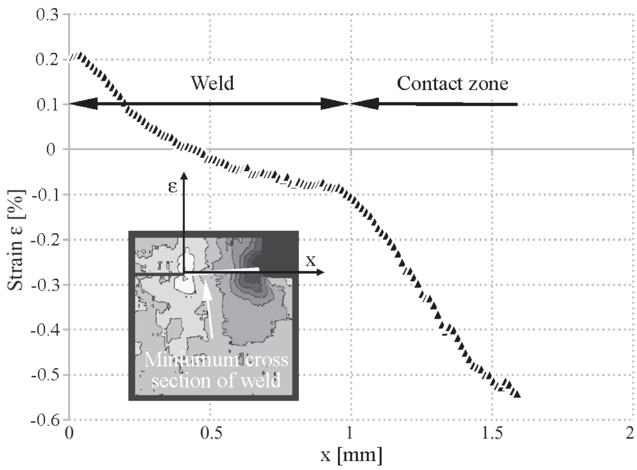


***Fig. 13.** The strain distribution in the minimum cross-section of the weld, at P = 1.54 kN*

Due to lack of a firm connection between the structural elements in the contact zone the plastic strains in the native material, resulting from compression remain unchanged, however the strains in the weld itself become smaller, that additionally increases the strain concentration effect in the heat affected zone during unloading the specimen.

The analysis of the strains in U-direction shows that they are symmetrically distributed with respect to the line running through the weld cross-section of the minimum area (Fig.14).

After detail analysis of the typical strain distribution shown in Fig.14.a, it was possible to suggest a probable character of the deformation of the joint containing laser weld, which is schematically shown in Fig.14.b. The web, while displacing relative to the shell plating, makes the laser weld formed of the material hardened due to welding process, rotating. The weld – while rotating – develops bending of the plate, manifested by two zones : of compressive and tensile strains, respectively, in the plate and web material on both sides of the weld. As a result, in the heat affected zone the strain gradients similar to those in the case of the strains in V-direction, appear.

CONCLUSIONS

- The investigation method applied in this work makes it possible to effectively determine strain distributions in the specimens of steel sandwich panels. The limitations associated with the exceedance of the basic measuring range of the method can be removed by using a sequential measurement procedure for the web and shell plate separately.
- The obtained strain distributions revealed much lower bending stiffness of the laser weld against the surrounding material, that made the entire joint more prone to deform. Due to a mutual „rotation" of the joined elements their edges (boundaries) come into mechanical contact in a short time.
- The contact phenomena revealed during the tests and the resulting asymmetrical behaviour of the joint imply to be very cautious in using the finite element method for modelling structural behaviour of the objects containing such joints. Application of the rutine approach and typical finite elements for structural analysis of such objects may lead to erroneous, and even unsafe results.
- In order to relate the observed effects associated with the developing of strain gradients to estimation of fatigue life of welded joints it would be necessary to perform a comprehensive fatigue test program covering, a.o., determination of weld-zone material properties under cyclic load and their changes during the testing. An analysis of the test results would make it possible to verify the present approach to the traditional welded joints. Knowing the local state of strains in the weld one would be able to apply the strain or energy approach to calculation of fatigue life of structures.

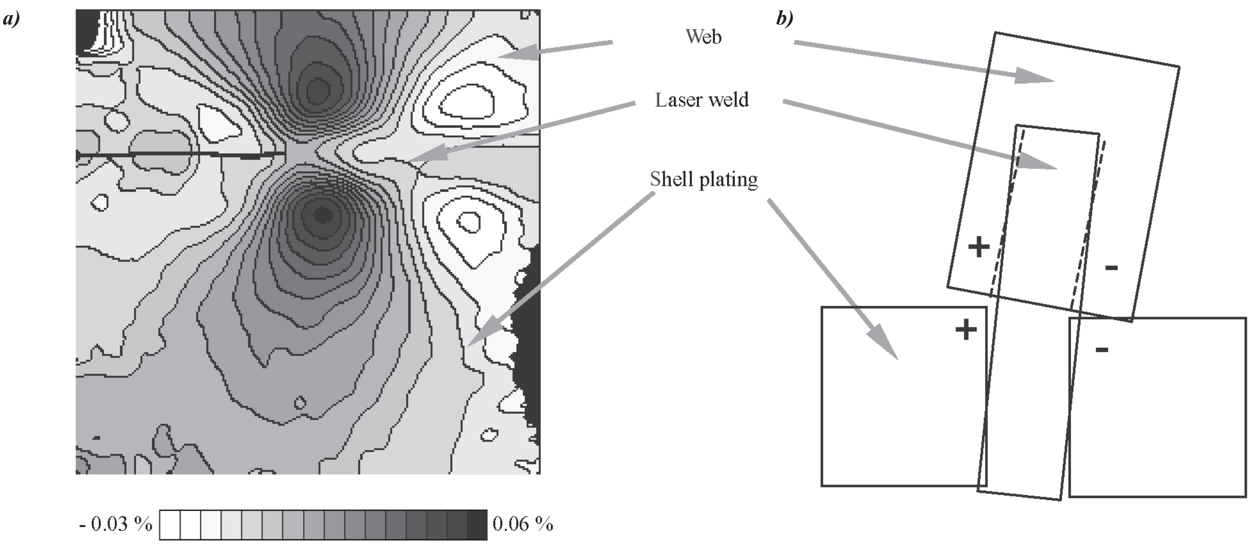


Fig.14.** Strain distribution in U-direction **(a)**, and scheme of deformation of the joint **(b)

ACRONIMS

ASPIS - Application of Steel Panels into Ship Structure
EMAS - Publisher
FEM - Finite element method
FPSOs - Floating Production, Storage and Offloading Units
IIW - International Institute of Welding
IRCN - Institut de Recherches de la Construction Navale
LES - Laser Grid Extensometer
MAG - Metal - Active - Gas
NASA - National Aeronautics & Space Agency
RINA - Royal Intitution of Naval Architects
SEM - Society for Experimental Mechanics
TWI - The Welding Institute
VTT - Valtion Teknillinen Tutkimuskeskus

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CONTACT WITH THE AUTHORS

Dariusz Boroński, D.Sc.
Mechanical Faculty
Academy of Agriculture & Engineering
85-796 Bydgoszcz, POLAND
Kaliskiego 7
e-mail : daborpkm@atr.bydgoszcz.pl

Janusz Kozak, D.Sc.
Faculty of Ocean Engineering
and Ship Technology
Gdańsk University of Technology
Narutowicza 11/12
80-952 Gdańsk, POLAND
e-mail : kozak@pg.gda.pl

FOREIGN conference

Maritime Transport 2003

On 25÷28 November 2003 in Barcelona
2^{nd} International Conference on :

Maritime Transport & Maritime History

organized by Department of Nautical Science and Engineering, Technical University of Catalonia, and Maritime Museum in Barcelona, had place.

During the Conference 72 papers were presented.

Most of the papers (14 and 9) concerned maritime transport and environmental protection, whereas 5 presentations reminding maritime history which allows understanding ways of development and contemporary state of the art of the maritime knowledge and activities, deserved special attention. The presentation was enriched by visiting the Maritime Museum.

Two sessions were carried out in Tarragona where the Conference participants had the occasion to visit the local Mediterranean port tightly connected with the important Spanish petrochemical complex and industrial centre.

Prof. W. Galor of Maritime University of Szczecin (Poland) took part in the activity of International Scientific Committee of the Conference; he also chaired one of the sessions on "Simulators and control systems" and presented - during the session on "Training and simulations" - the paper on : "*The navigational analysis of modernization of Łeba port entrance*".

Moreover, during the session on "Ship development and hydrodynamics" dr. Józef Kozak, Gdańsk University of Technology (Poland), read the paper on : "*Strength tests of steel sandwich panels*".