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Forecasting of fatigue life of laser welded joints

Keywords

Steel sandwich panels, fatigue life, strength properties, laboratory tests.

Słowa kluczowe

Stalowe panele „sandwich”, trwałość zmęczeniowa, własności wytrzymałościowe, badania laboratoryjne.

Summary

All steel, laser welded sandwich panels are recently considered as new structural material in different constructions – like aircrafts, inter-modal cargo transport media, civil engineering or shipbuilding. To apply such idea in wide range, knowledge about its strength properties for different combinations of load and boundary conditions is necessary. In the paper background information for steel sandwich structure is presented. Results of laboratory tests of fatigue life of elementary, laser-welded T-joints are presented. In particular properties which strongly influence static as well as fatigue strength of such joint are discussed in details. Natural scale tests of fatigue behaviour of large, laser welded steel structure – which are also presented in the paper – have given baseline for formulation of cracking model for different geometries and boundary conditions. Presented results allow to define the proposal of procedure for prediction of fatigue life for two skin, all steel, laser welded sandwich panel. On the basis of presented laboratory specimen test results, exemplary S-N design curve as crucial data source for described procedure is proposed for one of possible cases of cracking – as a mean for predicting fatigue life of laser welded steel structure.

1. Introduction

The laser welding technique – new idea, which went out from laboratory testing phase – is currently being applied on industrial scale in shipbuilding. Such

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technique offers new and interesting possibilities, because application of the laser welding processes create new opportunities of changing a configuration of typical ship structure by application ideas and designs reserved so far for glass reinforced plastic structures – two shells connected by internal system of thin stiffeners. Replacement of the “classical” ship hull design consisting of shell plating supported by perpendicular system of heavy stiffeners by such new structure requires knowledge of its characteristics such as strength, corrosion, vibrations, fire resistance and among others – fatigue. Such data are baseline for tools for assessment of fatigue life of new designed structure to prove to classification societies, that its properties are not worse in comparison to the classical one [1].

Basic types of sandwich structures (I-core) consists of the steel or aluminium panels fabricated as two shell plating of thickness from 1 to 6 mm each, with distance between them from 40 to 120 mm, connected and stiffened by system of uni-directional stiffeners with 40–120 mm span, using the laser welding applied from outside of shell plates and creating welded joint through the whole thickness of plate. Application of the sandwich structure, instead of conventional one (Fig.1), can give about 34% weight reduction and about 50% reduction of the manufacturing costs [2].

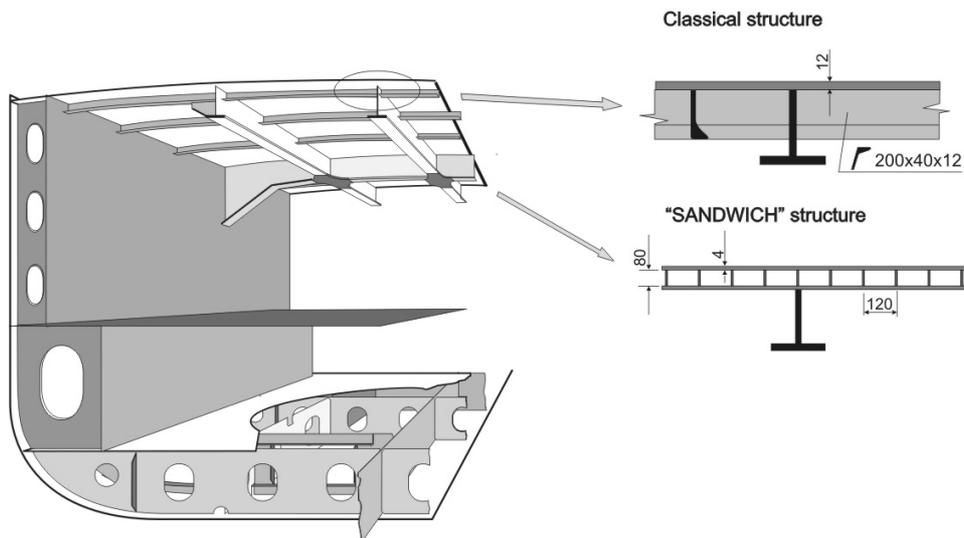


Fig. 1. Deck structure of ship: conventional and I-core sandwich type
Rys. 1. Konstrukcja pokładu statku: konwencjonalna i z użyciem paneli sandwich

2. Specific properties of laser welded T-joint

Laser welded T-joint – which is present in all steel sandwich panels – differs significantly from conventional MAG fillet welded one. Laser welded joint is formed by heat generated by light beam acting from outside of shell plate and forming needle-shape joint from melted metal of joined components. Cross sectional area of laser weld is significantly smaller than thickness of joined stiffener. Additionally – independently of how high quality of welding process is – the gap between stiffener and adjacent plate always occurs as a result of manufacturing process. Typical cross section of laser welded T-joint is presented below, where above listed properties are shown (Fig. 2a).

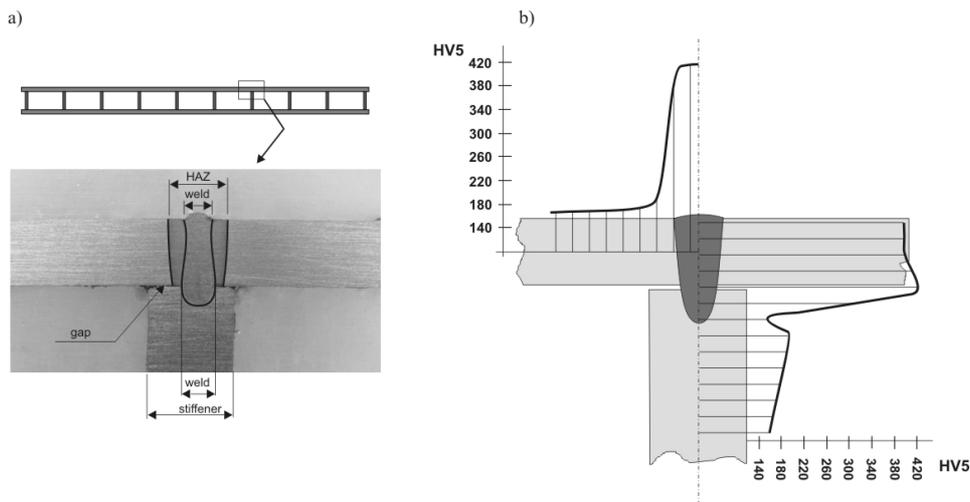


Fig. 2. Properties of laser welded T-joint: a) geometry of joint, b) hardness distribution

Rys. 2. Cechy połączenia teowego spawanego laserowo: a) geometria złącza, b) rozkład twardości

Such features suggest that laser welded T-joint is more sensitive to transverse bending moment than "classical" joint. As additional effect of that sensibility - contact processes between faces of stiffener and shell plating can occur. High gradient of hardness distribution as an indicator of presence of local stress concentration due to structural non-homogeneity is observed (Fig. 2b). Above mentioned properties suggest radically different fatigue properties in relation to classical T fillet welded joint.

Transverse dimension of laser T-joint presented in Fig. 2 in section of stiffener face is equal to 1,2-1,5 mm, whereas gap between face of stiffener and shell plate is equal 0,2 mm. Peculiarities mentioned above lead to conclusion that process of modelling of such geometry by Finite Element Method (FEM) - for determination of stress distribution - has to be carried out on significantly

higher level of details than for classical welded joints. To obtain more detailed information on deformation of joint, some investigations for description of deformation field of bended laser welded joint have been carried out. Results obtained on laboratory tested specimen using of the Laser Extensometer Technique (LES) proved complex behaviour of joint under bending load. Beside of the presence of tension strain zone, wide compressed strain zone also occurs. Occurrence of the contact process are responsible also for shifting of the neutral axis in weld bending – Figure 3 [3, 4, 5].

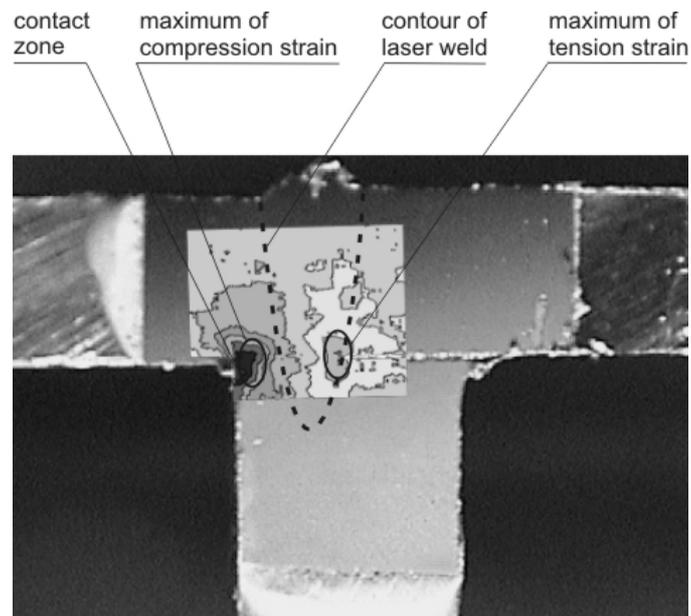


Fig. 3. Strain field in bended laser welded joint [3, 4, 5]
 Rys. 3. Rozkład odkształceń w złączeniu spawanym laserowo [3, 4, 5]

Study of the presented strain field distribution shows that – due to contact process - maximum compression strain value is almost twice higher in relation to tension strain one.

3. Assessment of fatigue life for all steel I-core sandwich panels

Several approaches to fatigue strength calculation have been proposed in literature – based either on the concept of nominal stresses, “hot spot” stresses, notch stresses or deformation criteria – Figure 4 [6]

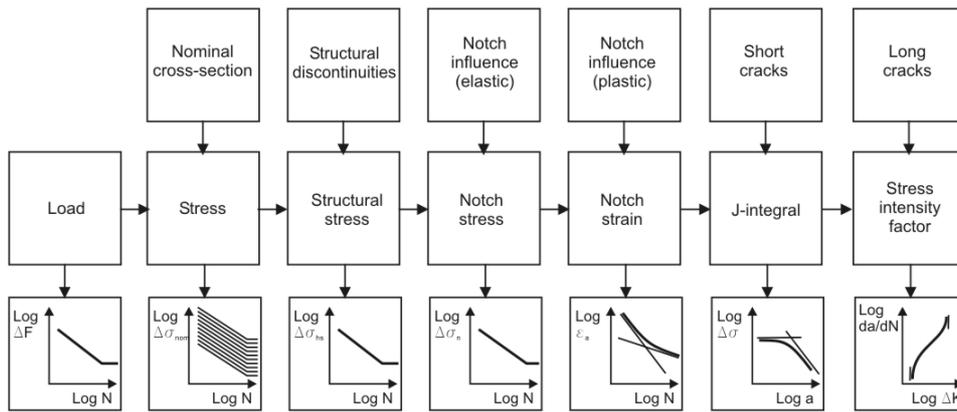


Fig. 4. Approaches for fatigue life calculations [6]

Rys. 4. Podejścia do prowadzenia obliczeń zmęczeniowych [6]

Analysis of the all steel, laser welded panel of two covering plates with stiffeners perpendicular to the shell proved, that geometry of laser created connection is always almost the same – independently on panel macro-scale dimensions. These stable geometrical characteristics of laser weld are the result of very high accuracy and strictly controlled laser weld process. The only discontinuities which can occur are related to specific characteristics of laser welded T-joint – as it was discussed in chapter 2. The sandwich panels are – because of its structure and especially thin plates – significantly more sensitive to influence of peaks of internal stresses caused by structural or technological factors on the local level. It can be - among others - local shell plating distortions caused by inappropriate assembly procedure or simply by poor quality of transportation process, or - for instance – by shifting of axis of laser weld in relation to the stiffener axis. Such concentration of stresses does not appear on regular basis and is impossible to predict, so it is unreasonable to incorporate them into fatigue life assessment procedure. Their influence can be taken into account by application of proper manufacturing tolerances. Calculation procedure should be based on data for structure manufactured accordingly to assumed tolerances.

Laboratory tests of natural scale steel sandwich, I-core panels - carried out by the author under different configurations of fatigue load and boundary conditions – have indicated, that such structure can be destructed by fatigue process in one of the following ways (Fig. 5) [7]:

- type 1: in laser weld toe in tensile shell plate, in direction parallel to stiffener, as the result of tensile stresses caused by global bending,
- type 2: in laser weld toe in tensile shell plate, in direction transverse to stiffener, as the result of tensile stresses caused by global bending,
- type 3: in shell plate as the effect of stresses caused by local bending or buckling,

- type 4: in laser weld in contact area between shell plate and stiffener face as the result of transverse rotation of shell plate,
 type 5: in laser weld in area between compressed plate and stiffener face caused by shear forces as the result of global bending.

Occurrence of each given case of crack configuration depends on applied boundary conditions and geometrical characteristics of the structure.

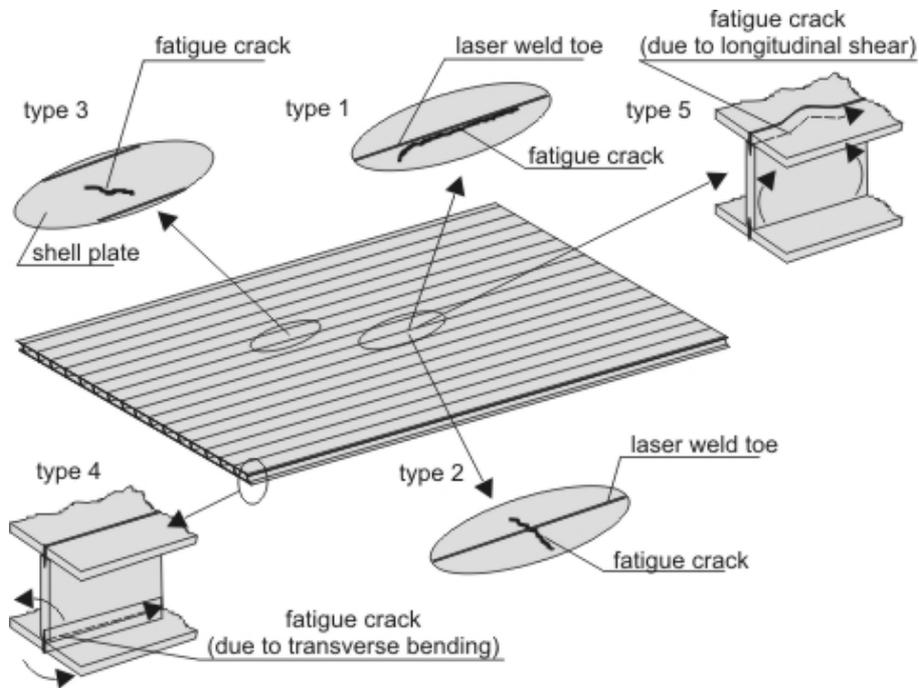


Fig. 5. Fatigue crack cases in steel sandwich panel [7]

Rys. 5. Sposoby niszczenia zmęczeniowego stalowego panelu „sandwich” [7]

Hence it is possible to formulate procedure for assessment of fatigue life of steel sandwich structures basing on nominal stress approach, which should consist of the following steps:

1. Modelling of strain & stress distribution
2. Selection of the mechanism determining crack development
3. Selection of the model of cracking
4. Definition of the reference value of nominal stress for calculations
5. Selection of proper design curve
6. Calculation of the fatigue life basing upon design curve.

Significant benefit for calculation process according to the proposed algorithm is, that one has to have a limited set of design curves – only one for each case of mechanism of failure presented in Figure 5.

The only problem – at the moment – creates “type 4” according to Figure 5, because such mechanism of destruction is controlled more by deformations rather than stresses. For the all remaining cases, the most important is proper selection of reference stresses value – which should be the same for definition of design curve as well as for calculation process. Design curves can be determined based upon systematic laboratory test of elementary specimen. Uncertainties like smallest scale of specimen, impact of the remaining part of the structure, changes in mechanism of failure during the process of cracking and other factors can be taken into account by application of the correction factor (safety factor).

The attention should be given to the proper assessment of the reference stresses in real structure. It can be done in different ways: direct calculations or by using FEM. Attention should be paid to results obtained by FEM because of its interdependence from model applied for FEM calculations [8].

4. Proposal of the design curves

Application of the proposed procedure requires of possession of set of design S-N curves, representative adequate to failure mechanism. Collecting data, processing and determination of such curve have to be based upon results of systematic fatigue tests carried out on specimen representing proper failure mode and reference stress level. Such results give baseline for statistical elaboration of S-N diagram.

As an example – process of determining of the design curve for the failure mode marked as “type 2” in Figure 4 is presented. As a data source - series of systematic laboratory tests of specimens under fatigue load have been performed. Specimens comprised part of laser welded T-joint directed parallel to the load direction – with the same material and thicknesses as “basic” model. Tests were carried out on series of specimens tested at five levels of load - according to the Standards. Tests were carried out under sinusoidal load 5 Hz with coefficient asymmetry of load cycle $R = 0$. Geometry of specimen is presented in Figure 6. Detail results from the tests approximated with linear regression line (inverse slope exponent $m = 4,61$, coefficient of correlation $r = 0,79$) are presented in Figure 7.

Basing upon results obtained from the tests, design curve is proposed as line parallel to the regression line, shifted left by value “minus two standard deviations”. Such line describes test results with probability of 97,5% and is presented in Figure 8.

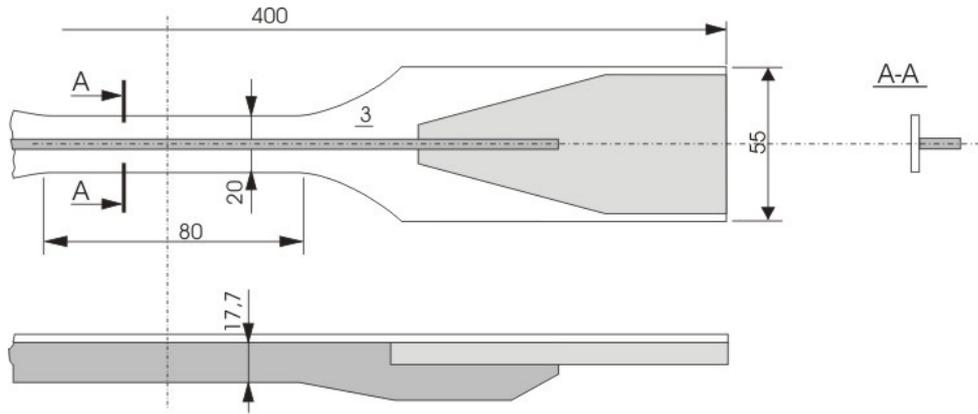


Fig. 6. Geometry of specimen
Rys. 6. Geometria próbki

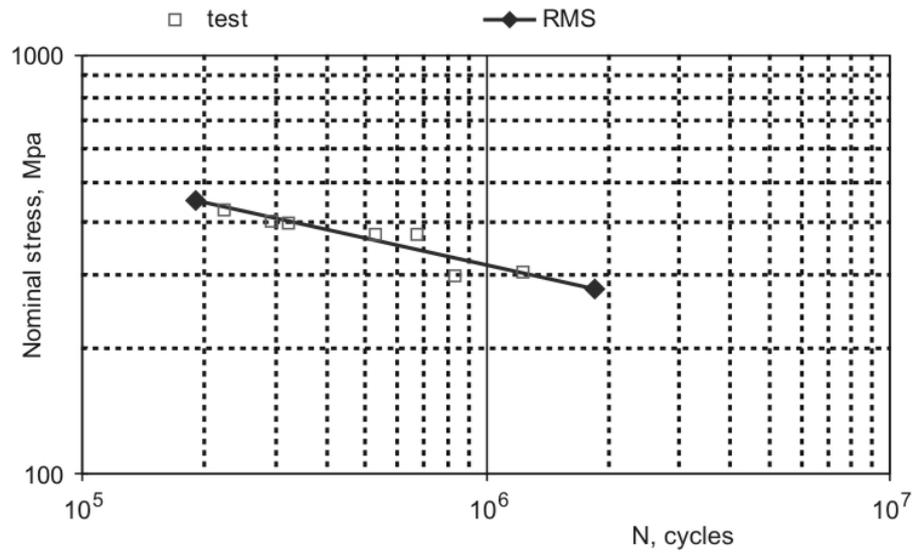


Fig. 7. Results of fatigue tests of laser welded T-joint
Rys. 7. Wyniki badań zmęczeniowych teowego połączenia spawanego laserowo

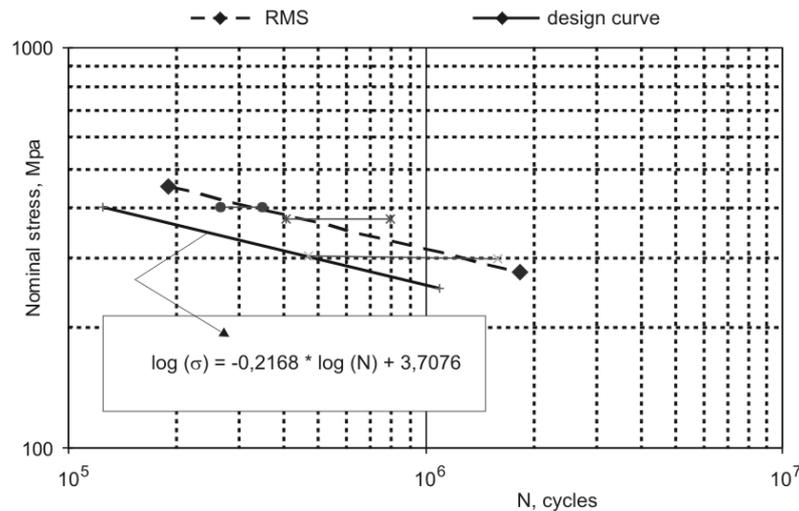


Fig. 8. Design curve for „2 type” of failure
Rys. 8. Krzywa projektowa dla „2-go” typu niszczenia

5. Conclusions

- Laser welded steel sandwich structures offer high potential both from the design, manufacturing as well as ship production point of view. In the paper specific characteristics of sandwich structure are presented and results of laboratory fatigue strength test of elementary laser welded joints results are described.
- Presented results indicate narrow scatterband of fatigue life data – it proves that the assumption made to use mean stresses for proposed algorithm was correct (assumption made basing upon very stable properties of laser weld).
- The five types of cracking can occur in sandwich structure. Occurrence of given case is determined by stiffness of the structure and its load and boundary conditions. Each type of failure presents particular fatigue crack locations and its development paths.
- Specific properties of laser welded T-connection: narrow width of the weld, the gap between face of stiffener and shell plate and high gradient of hardness distribution play significant role in fatigue behaviour of loaded joint.
- Results of tests of elementary specimen can be the baseline for fatigue calculation of real structure. Crucial problem for credible results of fatigue assessment is proper selection of reference stresses.
- Problem still open is the size of specimen usually used for obtaining S-N curve. Size of detectable and final failure cracks observed during fatigue tests performed on standard, small specimens is significantly smaller range than one one appeared in real structure.

Acknowledgement

This paper is based upon results of the works carried out within frames of European Union supported GROWTH FP5 “Advanced Composite Steel Sandwich Structures” – SANDWICH, G3RD-CT2000-00256’ and “Application of Steel Sandwich Panels into Ship Structure” – ASPIS – E!3074 EUREKA research projects.

Praca wpłynęła do Redkacji 24.01.2007 r.

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Przewidywanie trwałości połączeń spawanych laserowo

Streszczenie

Stalowe panele spawane laserowo zaczynają znajdować coraz szersze zastosowanie w różnych typach konstrukcji: przemyśle lotniczym, w obiektach transportu lądowego, budownictwie lądowym czy wreszcie w konstrukcjach okrętowych. Aby móc stosować te nowe rozwiązania w szerokim zakresie, niezbędna jest znajomość ich własności wytrzymałościowych dla różnych wariantów obciążenia i warunków brzegowych. W pracy przedstawiono podstawowe dane na temat stalowych paneli typu sandwich. Zaprezentowano wyniki testów zmęczeniowych elementarnych połączeń teowych spawanych laserowo. Omówiono szczegółowo te cechy, które mają istotny wpływ na statyczne i zmęczeniowe własności złącza. Przedstawiono również wyniki badań zmęczeniowych paneli sandwich w skali naturalnej, które pozwoliły określić modele pęknięcia takiej konstrukcji. Dało to podstawę do sformułowania propozycji szacowania trwałości zmęczeniowej dwupowłokowych, stalowych paneli spawanych laserowo. Na podstawie przedstawionych wyników badań zmęczeniowych elementarnych połączeń spawanych laserowo uzyskano krzywą projektową S-N dla jednego z pokazanych modeli pęknięcia. Krzywa taka jest istotnym źródłem danych w proponowanej procedurze. Zaproponowane podejście wraz z przykładową krzywą projektową może być narzędziem do przewidywania trwałości zmęczeniowej konstrukcji spawanych laserowo.