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Comparison of Strain Results at a Laser Weld Notch Obtained by Numerical Calculations and Experimental Measurements

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Abstract. In the development of ship structures applying new materials and it's purposeful placement play an important role. During the last years, especially in a construction of ro-ro type vessels, the usage of novel sandwich structures in cargo decks is profitable. Steel sandwich panel is an innovative solution which at a todays state of development can be used for the construction of any members not taking part in a global bending of a hull. The one important reason for this is a lack of knowledge and experience in the fatigue assessment. The problem of fatigue assessment of the steel sandwich structures arises from no typical welds connecting its structural components. The joints are fabricated by the use of laser welding technique, or hybrid welding. Standard methodology for the fatigue analysis is local stress approach or local strain approach. In both methods the crucial aspect is determination of a maximum values of strains and stresses. The most effective technique to designate these values is numerical modelling with the use of Finite Element Method or Boundary Element Method. In this paper the comparison of local stresses at a weld notch obtained by two independent methods is presented. The results calculated by the Finite Element Analysis are being compared with the experimental one measured by the use of laser extensometer grid technique. The goal of this comparison is verification of the main numerical modelling assumptions.

1. INTRODUCTION

In the context of global market economy the maritime transport plays a role of huge importance. It is estimated that about 90% of world trade is carried by ships. In the last decade significant development of the water means of transport took place. Both the advances in material properties as well as improvements in a structural design of a ship are equally important. It has to be marked that new solutions in ship industry used to be introduced very slowly with conservative approach and limiting a risk. The tendency of any changes in a ship design have much more evolutionary than a revolutionary character. Any attempt of inducting radical changes in a ship construction most often is associated with not acceptable level of risk. Despite that in recent years a new form of ship structure has been introduced into the industry – sandwich panels. It is a type of structure consisting of two thin plates connected by internal stiffeners. The thickness of plates and internal stiffeners is between 1.5 - 4 mm. Especially internal stiffeners occur in different shapes and forms. The materials used are high strength steel and different aluminum alloys. The main advantage of the metal sandwich structure is very high strength and stiffness in relation to its weight. Particularly important is a very high stiffness of a transverse cross section in relation to its advantageous and compact overall dimensions. The all metallic sandwich panels are being used in many different industrial branches. In a ship building industry the solution has found numerous applications i.e. for the decks of the ro-ro ships. Nevertheless the industrial utilization of steel sandwich panel solution is currently limited to the structural members not directly carrying a global bending load of a hull. Considering laser welded steel sandwich panels this limitation results mainly from difficulties in proving adequate fatigue resistance of joints connecting plates with internal stiffeners. Thus the steel sandwich panels at a

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present state of art are new solution which requires individual approval for a specific application case. The process usually involves verifying fatigue properties of a structure by industrial research (FEA and/or experimental testing).

The problem of fatigue assessment arises mainly from very unusual welding technology of very thin structural members. The connections between plates and internal stiffeners are fabricated by laser welding technique, or hybrid welding technique. It leads to fabrication of a connection having very untypical geometry and material properties. The fatigue assessment of such welds can be conducted on the basis of local fatigue approach – local strain, or local stress methodology [1, 2, 3]. In both methods the most effective tool for the determination of local strains and stresses is carrying out the numerical analysis with the use of Finite Element Method or Boundary Element Method. The methodology of performing fatigue calculations including the guideline of making modelling assumptions has been well developed for all typical joints. Namely the welds fabricated by conventional welding technology and having the thickness above 5 mm. Also only a standard geometry is considered. Most often it is a butt weld, or a fillet weld joint. Whereas for untypical welds, particularly connecting thinner plates there is no specific guideline for carrying the fatigue calculations. Therefore the fatigue analysis of new type of steel sandwich panels welds requires detailed individual consideration. The photography of typical cross section of the weld is shown in Fig. 1.

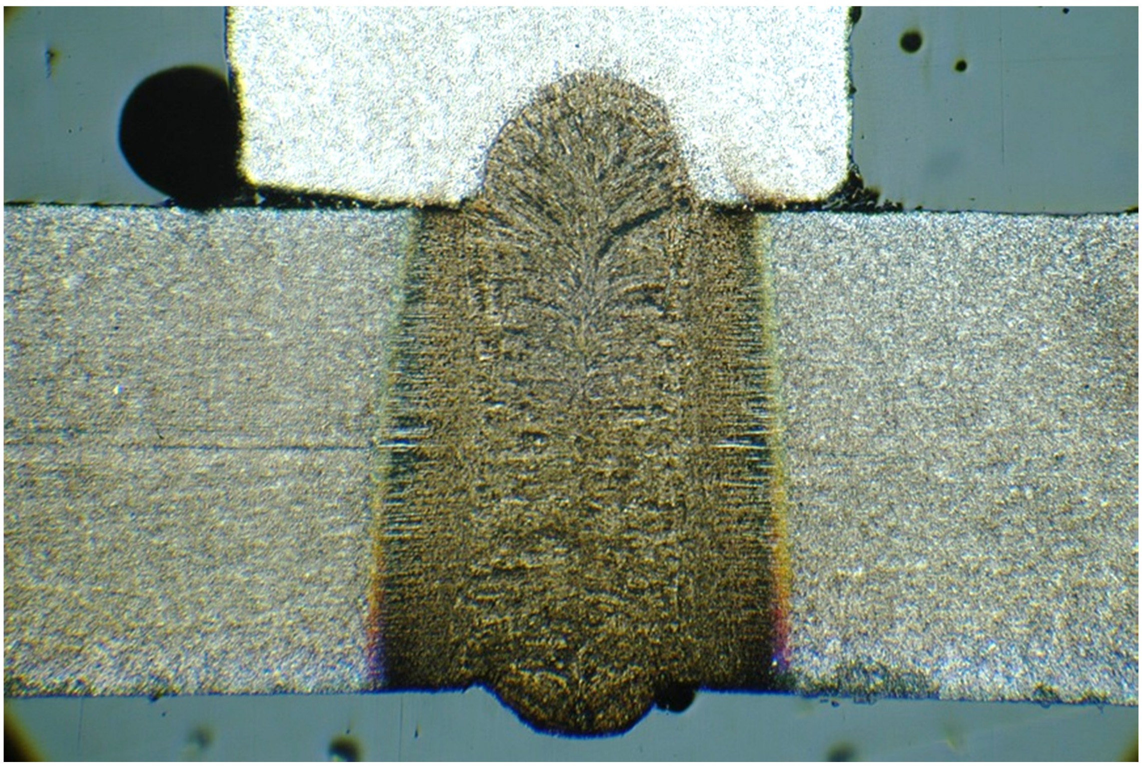

FIGURE 1. Typical cross section of laser weld of I-core steel sandwich panel

The numerical simulation for the determination of local strains at a weld area should analyze much wider spectrum of the modelling assumptions than in an analysis of typical joints. In this article the comparison of numerical results with the experimental ones is presented to verify an accuracy of the numerical modelling. In the following section no 2 the most important assumptions for the numerical modelling of a steel sandwich panel weld will be presented. In the following section no 3 the results of local strains calculated by the FEM modelling will be compared with the results acquired independently by the experimental measurements with the use of laser extensometer grid technique (LES).

2. NUMERICAL MODEL OF THE LASER WELD

The numerical analysis according to the local stress or strain approach for non-typical joints is problematic because of lack of a specific guideline for the several numerical modelling assumptions which have to be made. Nevertheless the computer simulation taking advantage of a Finite Element Method (FEM) is the most effective way for the determination of local strain and stress at an area of weld notch. Thus it was applied the methodology analogous to that of typical joints, but with examining the influence of the main modelling assumptions on the results. The most important aspects of the numerical modelling are: modelling approach, selection of finite elements, the geometric representation and discretization, loads and boundary conditions, material model, modelling of geometrical notches. In the following points the most important modelling assumptions will be discussed for the determination of local strains at a weld notch. The analysis was performed for a representative T-joint of steels sandwich panel structure.

2.1. Modelling approach, selection of finite elements

The numerical model was built in the ANSYS software. Detailed analysis of modelling approach on results was presented in an article [4]. The research shows that for considered issues the optimal selection of modelling is two dimensional approach in a plane strain state. The obtained results of strains are very similar to these calculated by three dimensional model, but with much improved efficiency of the analysis. It has significant practical importance because the analysis with the use of two dimensional models and 4-node or 8-node finite elements can be performed on standard PC class work station. Whereas effective numerical analysis in three dimensional state of strains and stresses requires the use of much more computing power. In the numerical model presented in this paper the PLANE82 finite element was used. It is a 8-node element having two degrees of freedom in nodes. The influence of a mesh refinement on results of local strains and stresses at a weld notch was presented in work [4]. It was concluded that an optimal mesh refinement should be performed up to obtaining the ratio of FE edge length to the toe and root notch radius equals 0.07 and 0.02 respectively. Further compacting of finite elements leads only to unjustified increase of a model size. In the other hand usage of coarser discretization can leads to not acceptable simplification of the geometry and results in inaccurate values of local strains and stresses.

2.2 Geometry, model discretization

The geometrical dimensions were acquired by optical measurements on a photography in x100 magnification scale. The work was performed on 6 representative samples collected from steel sandwich structure and the results were averaged. Next the mean values of the geometrical representation were applied in the numerical model of a laser weld. A single joint between plate and stiffener is shown in Fig. 2. During discretization of a model an automatic meshing algorithms were used. The intention of that was to enable to benefit from an associative parametric definition of a weld geometry. The efficient model written in APDL code was used for the research on the influence of parameters on results. The definition of parameters for the division of lines and surfaces enabled maintaining high quality mesh during very fast and fully automatic rebuilding of a model. Naturally it is possible to improve a mesh quality by manual adjustments. However for the presented range of calculations it was not necessary and the main quality parameters of the mesh were fulfilled.

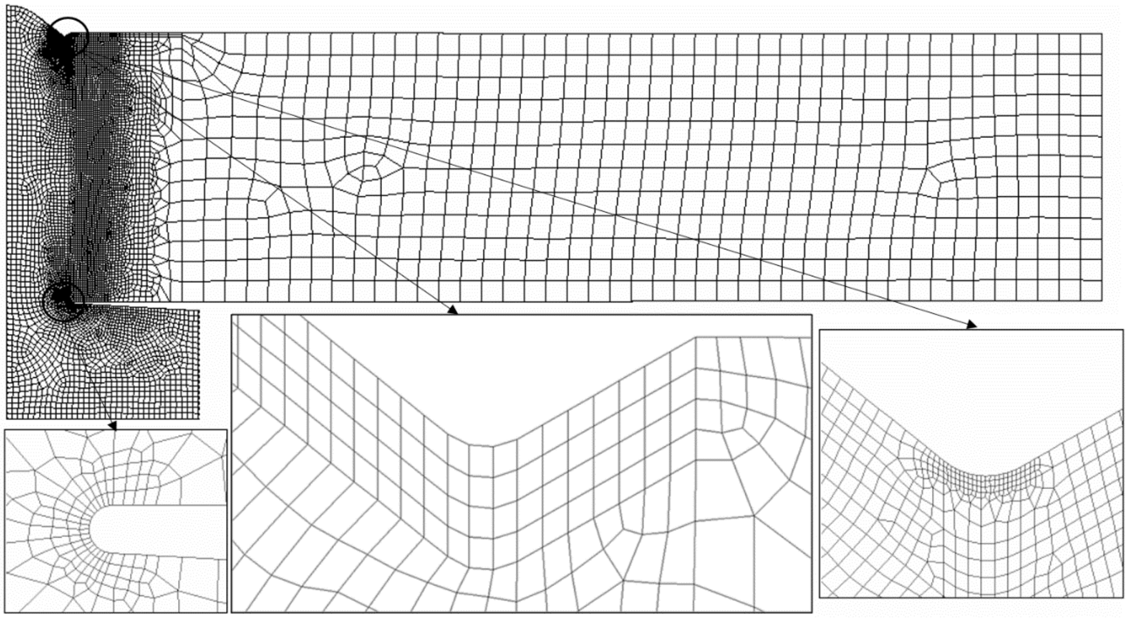

FIGURE 2. The geometry of FEM model with notches

2.3 Loads and boundary conditions

The analysis considered primary load condition – tension in a plate of sandwich panel. The symmetry of geometry and loads was assumed. The force was applied to a plate in a distance from analyzed weld area to ensure a uniform distribution of the nominal load. The concentrated force equal the nominal load of σ_x=268 MPa was applied to the plate edge (Fig. 2). The value of nominal load was equal to the one used in an experimental testing for the determination of local strains at the notches. Moreover a similar analysis was performed for other values of the nominal load but none unusual distribution of strain and stress were observed. Thus the representative results for the one value of nominal load are presented in this article.

2.4 Material model

The laser welds of steel sandwich panels have non-usual distribution of material zones at the area of weld. The weld material zone is very narrow and elongated while a heat effected zone is extraordinary narrow. For a connection of plates having thickness of 2.5 mm the total width of a joint, the width of a weld zone, the width of a heat effected zone is equal 3.53 mm, 3.18 mm, 0.35 mm respectively. Very narrow weld zones result in presence of high gradient of the material hardness - much higher than in welds fabricated by the use of standard welding technology. There is therefore a question of the influence of non-typical material hardness distribution on strain and stress state. Though the maximum value of strain and stress has crucial influence on calculated fatigue life of a joint. The results presented in this article were obtained by the numerical model of the laser weld having three material zones with assigned material properties determined in [5,6]. The stress-strain curves for particular material zones of a weld are shown in Fig. 3.

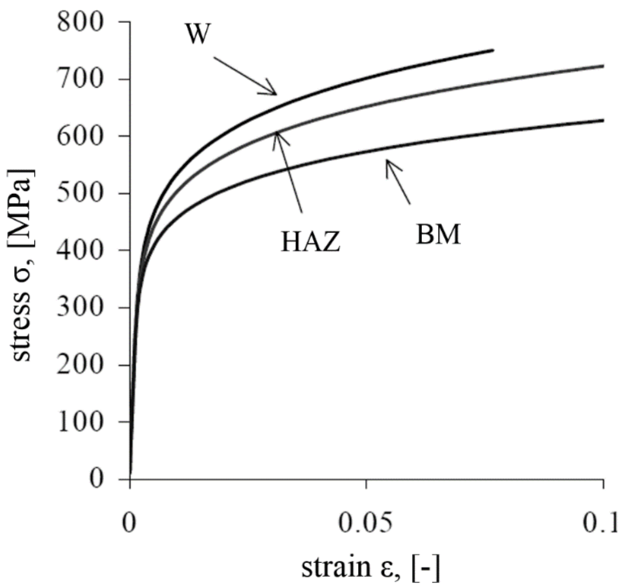

FIGURE 3. The stress-strain curves for material zones of the laser weld (W-weld, HAZ –heat effected zone, BM – base material) [5, 6]

The influence of modelling method of particular material zones on the results was discussed in the article [7]. The most important result of this analysis was to demonstrate that taking into account the effect of presence of some of the material zones is not mandatory. The value of maximum strain or stress is an effect of presence of the geometrical notch. Unusual shape and dimensions of material zones has very limited impact on a strain and stress distribution. The effect of geometrical notch has very local character with an influence zone equal up to the 4-times of a notch radius. The simplification of numerical modelling to the one material zone, having the parameters of weld zone, in a significant manner accelerates and simplifies performing the numerical analysis. Thus the key conclusion from the analysis of an influence of material numerical model on results is as follows. The strain and stress concentration results from a geometrical notch and there is no presence of an additional so called 'material notch'. It enables the application of local strain and local stress approach to the fatigue analysis of the steel sandwich panel laser welds.

2.5 Modelling of geometrical notches

The methodology of performing fatigue calculations by local approaches assumes the averaging of the maximum value of strain or stress in some distance from a notch bottom. For the purpose of this at the place of geometrical notch there is put in a rounding or a circle concentrator having radius equal to the calculated fictitious notch rounding [1]. In the article [8] the analysis of influence of the parameters of a notch geometry on strain and stress results can be found. Nevertheless the results presented in this article were obtained with the use of modelling a weld in a direct way. It means that the geometry of a notch was modelled as measured from real scale sample. The only assumption was applying a rounding at a root notch with a diameter of a gap between plate and stiffener. This simplification was necessary because of a practical requirement of the model discretization.

3. THE COMPARISON BETWEEN THE NUMERICAL AND EXPERIMENTAL RESULTS OF LOCAL STRAINS AT A WELD NOTCH

The comparison of strain results at a weld notch obtained by two different and independent methods was performed. The first method was a computer simulation carried out by the author with the use of a Finite Element Method (FEM). The second method which was used to verify the numerical results was a laser extensometer grid technique (LEG). The experimental research was performed with a cooperation of Prof. Józef Szala and Prof. Dariusz Boroński from University of Science and Technology in Bydgoszcz. The most important aspects of a numerical modelling were described in previous points of the article. The potential influence of numerous assumptions of the numerical modelling on the results can be substantial and induces to the verification. Therefore it was performed the comparison of local strains at a weld notch calculated by the numerical calculations with these measured by experimental testing. The analysis was performed for a nominal load of σ_x=268 MPa which was the highest one from all being considered during the experimental research. For this load in a weld notch a plastic strain was present. The values of measured strains for the maximum load is presented graphically in Fig 4 below.

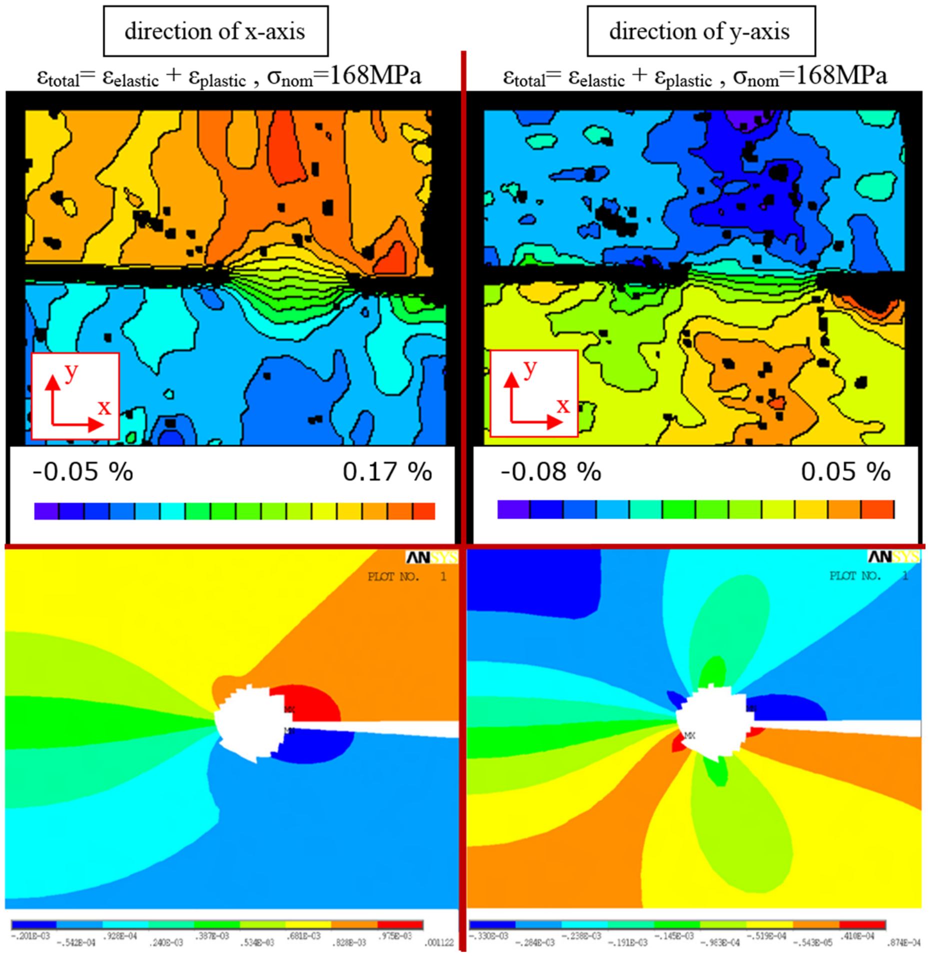

FIGURE 4. Local strain at a weld notch area measures by the laser extensometer grid technique (first row) and calculated by finite element method (second row)

The comparison of strains were performed on the x-axis which is horizontal and parallel to the panel plate and on the perpendicular y-axis. The plot of results calculated from the numerical simulation were limited by excluding from the analysis elements inside the circle having radius of r=0.15 mm. Such approach was caused by two reasons. At first according to the local stress averaging approach by

substitute microstructural length for the analyzed material this is the proper distance for determination of maximum averaged stress value [1]. The second reason was to enable comparison of local strains at close vicinity to the geometrical notch instead of at the notch edge. Excluding from the analysis the edge of geometrical notch arises from practical consideration of interpretation the experimental results.

Namely the strain values measured by the LES method at the edge of geometrical notch can lead to misinterpretation. At the edge the plot of strains has areas where a measurement limit defined by the diffraction grating was exceeded. Thus at a weld notch bottom a very local strains surpassed the bound of measurement technique and the results should not be compared. Beside this area the plots of experimental and numerical results are very similar. In the x-axis direction (parallel to the plate) there is a tensile strain in a panel plate, while at a stiffener there is a compressive strains dominating. Whereas in the y-axis direction (perpendicular to a plate) there are compressive strains in a panel plate, while in a stiffener tensile strains are dominant. For the fatigue assessment of great importance is a maximum value of strain at a notch area. Therefore the competition of strains was performed in x-axis and y-axis direction in a distance of r=0.15 mm from the center of circle circumscribing a notch shape. The results of measured and calculated values of strains in x-axis and y-axis direction are combined in Table 1 below.

TABLE 1. Comparison of the results obtained be the numerical calculations (FEM) and by the experimental measurements (LES)

	Experiment (LES) ε_{total_LES} [-]	Numerical calculations (FEM) ε_{total_FEM} [-]	$\frac{\varepsilon_{total\_LES} - \varepsilon_{total\_MES}}{\varepsilon_{total\_LES}}$ [%]
Value of $\varepsilon_{total}=\varepsilon_{elastic}+\varepsilon_{plast}$ in x-axis direction, averaged in a root notch [-]	0,05e-3	0,046e-3	7
Value of $\varepsilon_{total}=\varepsilon_{elastic}+\varepsilon_{plast}$ in y-axis direction, averaged in a root notch [-]	-0,014e-3	-0,012e-3	10

The relative difference of total strains calculated as a sum of elastic and plastic strains in x-axis and y-axis direction equals 7% and 10% accordingly. Therefore it can be stated that numerical and experimental results are very similar. It confirms the correctness of the main modelling assumptions of the laser weld. Moreover the methodology of determination of the local strains according to the local approaches assumes applying a rounding or circular concentrator at a place of geometric notch. It significantly reduces many of the problems related with determination of maximum values of strains at a weld notch. Using the technique of averaging values in a substitute distance from a weld notch as well as the technique of applying fictitious notch rounding leads to determination of very similar results.

4. CONCLUSIONS

The presented research enables to formulate the following conclusions:

1. In a case of the analysis of non-typical joints the determination of local strains and stresses at a weld notch by computer simulations is very time-consuming and labor absorbing. The analysis of the influence of many modelling aspects on the results is required. In this article the most important aspects of modelling by the finite element method were presented for the laser weld of steel sandwich panel. The remarks about the influence of the most important modelling parameters on the results of local strains at a weld notch were presented.
2. The analysis of experimental results for the determination of local strains by the laser extensometer grid technique was performed. The research was performed in accordance with measurement procedure and very detailed results at weld notch area were obtained. However the limitation of the research method resulting from the resolution of the diffraction grating effected on the difficulty in results interpretation at a notch edge. The measured strains in a small area at the notch edge exceeded a measurement limit. These results were excluded from the analysis. At the same time the desirable results at the area in a distance of 0.15 mm from the notch bottom were determined. It enabled the verification of the results calculated by the computer simulation.
3. The results determined by experimental measurements and numerical simulations were very similar. Relative difference of maximum strains calculated by FEM method to the values measured be the LES method was equal 10%. It constitutes the confirmation of a proper numerical modelling and a very high accuracy of calculating the strains at the notch area of the steel sandwich panel joints. The comparison of results at the bottom of the notch was not possible due to the limitation of the diffraction grating used.
4. In the fatigue assessment by the local strain or stress approach during FEM calculations at the area of geometrical notch a rounding or a circular concentrator is placed. The intension of this is averaging the maximum calculated strains and stresses according to the microstructural notch support hypothesis by Radaj [1]. This technique has also very important advantage of excluding from the analysis the differences of a notch

shape which often exist in practice. Thus the fatigue analysis according to local strain or stress approach with the use of substitute model of a notch topology is recommended.

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