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PREDICTION OF WELDING-INDUCED DISTORTION OF FIXED PLATE EDGE USING DESIGN OF EXPERIMENT APPROACH

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ABSTRACT

The paper presents the results of experimental studies on distortion of the fixed plate edge due to formation of a butt joint. This is a hidden form of weld distortion present in structural nodes and identified at the ship hull pre-fabrication stages. The investigations were performed according to a design of experiment (DoE) approach in laboratory conditions resembling those encountered in the shipbuilding industry. The presented analysis includes the technological-construction parameters influencing the evaluated distortion shape. The implemented method of experimental results evaluation allows the utilisation of the approximation dependence to predict the fixed plate edge distortion in large-scale steel structures.

Keywords: weld distortions, fixed plate edge distortion, designed experiment, prediction models

INTRODUCTION

The most disadvantageous phenomena associated with the welding process are distortions of combined construction elements. These are weld distortions, which significantly degrade the quality of pre-fabricated technological sub-assemblies in all kinds of large-scale steel structures, particularly in ship hulls, and refer especially to those fragments of structures that comprise thin-walled plates, for instance those used in the superstructures of seagoing ships (Fig. 1). One of the negative features of this solution is the tendency of such structures to deform upon welding. This is directly connected with the presence of actual deviations (deformations) exceeding acceptable tolerances (acceptable from the standpoint of execution standards for large-scale structures, for example: [4, 18, 25]). In order to prevent this, some corrective actions are necessary, which significantly increase the labour consumption. It is estimated that, in the case of ship hulls, repairs to spatial sections and blocks constitute around 20–25% of labour consumption, which is equal to the contribution of the welding operations on the ship hull during the total period of ship-building [12]. Hence, proper design of these sections requires knowledge about weld distortions and their prediction.

The problem of weld distortions has existed since the implementation of welding as a method of joining construction materials. Effective prediction of the occurrence of distortions has always been one of the most important issues. The first scientific papers providing the fundamentals of distortions evaluation and prediction were written 70 years ago. They include the contributions of Rosenthal [21, 22] and Rykalin [24], describing the temperature distribution in the vicinity of a weld joint using mathematical dependences. The papers by Okerblom [16, 17] provide formulae based on experimental investigations. Analytical methods pertaining to the theory of plasticity were employed by Watanabe and Satoh [31] to describe the formation of thermal distortions during welding and linear heating.

The progress in calculation techniques has also influenced the methods of distortion determination and prediction. Numerical methods such as the finite difference method (FDM) and finite element method (FEM) have played a significant role in this process. Both methods became very helpful in the modelling and analysis of thermal processes (mainly from the standpoint of physics). The pioneers who implemented them in weld joint science were Wetsby [32] (FDM, late 1960s) and Ueda [26] (FEM, early 1970s). The last three decades have witnessed progress in FEM, which has become a dominant tool in solving problems in metal connection physics [8, 9, 13, 19]. The authors focused mainly on the determination of the influence of heat flux on the final form of distortions in the description of the fundamental forms of distortion and in their prediction. Since the beginning of the current century, FEM has been utilised for the modelling of increasingly complex technical problems, verifying simulation with experimental results, for example in [1, 2, 5, 6, 10, 29, 30].

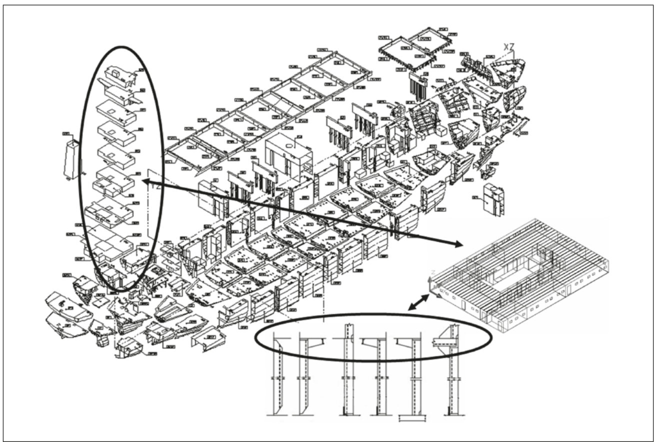

Fig. 1. Axonometric plot of ship hull with superstructure module illustrating typical structural nodes

Using numerical analysis in design applications, especially for large-scale structures, is time-consuming and expensive. That is why a more practical solution in design practice is the implementation of the models in analytical calculations dedicated to particular structural nodes, which allows the prediction of weld distortions using simple calculation tools. One of the most frequently applied physical models of ship structural nodes of thin-walled elements is a system of two linearly welded metal sheets, where one of the sheets is fixed at one edge [31]. For this type of support, the scientific literature lacks any results from investigation of the distortion of the fixed edge at the point of assembly, after release from the mountings. There is thus no mathematical prediction model taking into account fundamental technological-construction parameters relevant to the magnitude of the distortion form under investigation.

The aim of this paper is to elaborate a theoretical model, in the form of an algebraic equation, for prediction of the distortion of the fixed plate edge in shipbuilding practice.

The goal was achieved using the design of experiment approach. The method of predicting the investigated weld distortion form was based on analysis of regression models.

The models of welded plates fixed at one edge, which are analysed in this paper, find widespread application in ship construction. Fig. 1 presents typical structural nodes using the investigated model, especially related to the superstructures and other light deck structures (the nodes visible in Fig. 1 were adopted from [23]). The weld distortions investigated during the described experiment are revealed after releasing the object from the supports. In reality, this is a hidden form of weld distortion present in given structural nodes at the section pre-fabrication stage. In this case, shape distortions connected with the presence of internal bending moment are transformed into internal stress in the particular structural node. Its magnitude influences the resistance of the entire structure to external load applied. The level of internal stress generated often determines local fatigue phenomena in the given structural nodes during ship service. An example might be frequent fatigue cracking of the deck in the places where it is connected to the sheer strakes or to the supporting brackets. In order to mitigate these phenomena, methods that reduce the distortion of particular deck plates during the section welding process are applied. This is achieved by proper selection of the technology and technique of welding pre-fabricated section elements. In order to elaborate suitable technological recommendations, it is essential to possess a set of actual measured distortions of the structural nodes' elements, depending on the technological-construction parameters applied. The results of the investigations presented in this paper can be utilised in practical elaboration of the techniques for reducing weld distortions (see Fig. 2). On the other hand, knowledge of the magnitude of distortion for a particular structural node, acquired using the energetic methods employed in mechanical calculations, can be used to calculate the internal stress accumulated in the node due to the welding process.

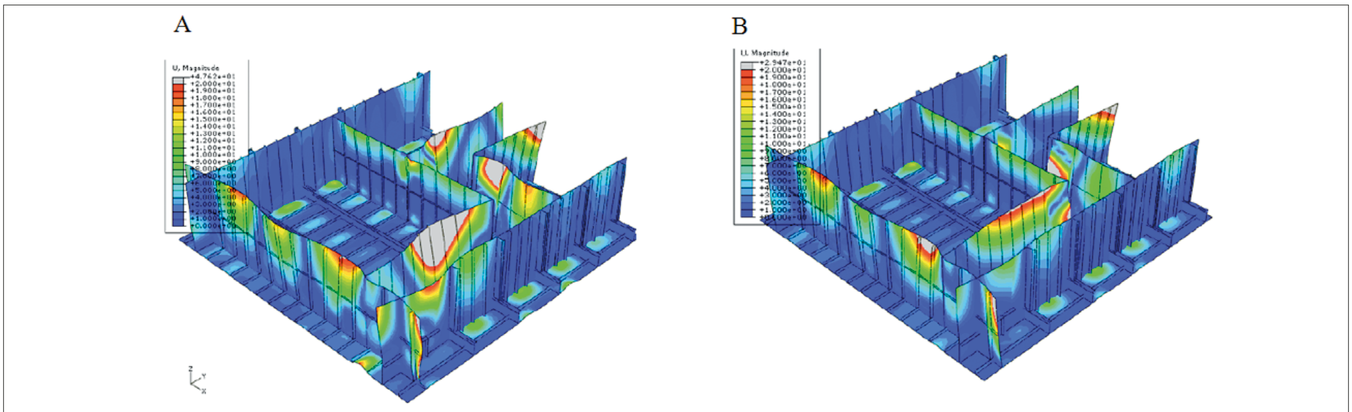

Fig. 2. Pre-fabricated section: A before -, B after – application of weld distortion reduction techniques [11]

EXPERIMENTAL INVESTIGATIONS

The experimental investigations were carried out in accordance with the designed experiment theory [14, 15]. A butt joint was considered as a so-called black box (see Fig. 3). The following selected technological-construction parameters determining the formation of the analysed distortion form (a dependent variable) were treated as the independent variables: the linear heat input of the welding process, steel plate thickness and welding gap. The black box of the designed experiment involves two more groups of quantities – so-called confounding factors and constant factors, which in the presented studies include, for instance, the thermo-physical properties of welded materials (the constant factors) and a human factor (a confounding factor). Due to the fact that the aforementioned groups of quantities are neither controllable nor measurable, their influence on the distortion was omitted during the studies. These two groups of quantities are contained in the result in a hidden form.

The experiments were performed based on the 3^{k-p} Box-Behnken design for three factors [14], in which the input values were changed at three levels (namely minimum, medium and maximum). An approximated function of the investigated object was a quadratic polynomial model with first order interaction terms, which in the general case takes the following form:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{\substack{i,j=1 \\ i<j}}^{k} \beta_{ij} X_i X_j + \sum_{i=1}^{k} \beta_{ii} X^2_i \tag{1}$$

where:
Y – matrix of dependent variables,
X_i, X_j – matrices of independent variables,
β_0, β_i, β_j – vectors of coefficients of investigated object function.

In the case of selecting three independent variables, the number of experiments in a single (required) block equalled 15 (depending on the data volume, a block of these 15 experiments can be executed many times). Minimum, medium and maximum values of the independent variables corresponded to a range of the technological-construction parameters employed in production conditions (see Table 1). The number of measurement repetitions for each design of experiment was $r_u \leq 3$, whereas the number of system repetitions, for verification of the investigated object function conformity, in the design centre was equal to $n_o \leq 5$.

The experiments were carried out in conditions similar to the production conditions, at the position being a fragment of a shipyard jig (see Fig. 4). The investigated materials were: AH 36 steel comprising the plates combined with a butt joint, and S355 and S235 steels for stiffened panel elements (sandwich panel I-core type). The object under investigation consisted of structural elements with different rigidity, so a laser-welded I-core panel was selected only as an element symbolising a piece of the structure with higher flexural rigidity than a conventional plate and with higher static strength than a conventionally stiffened panel. The steel plate and stiffened panel formed a structural node, which is shown in Fig. 4 together with the samples' dimensions. The butt joint was prepared using the FCAW method in CO_2 shield according to the industrial regulations [3] by a welder with several years of experience in the shipbuilding field.

Sample support elements, simulating assumed forms of boundary conditions, included a clamped support on the structural node and a fixed of the steel plate (Fig. 4). This situation is in accordance with the commonly adopted rules of large-scale steel structures (including ship structures) production technology. The stiffened panel substitutes a fragment of plating (for example, the superstructure's deck) that is unidirectionally conventionally stiffened (for instance with a flat-bulb section), to which the remaining elements of the construction can be fixed. Thus, the mounting of the panel (clamped support) represents a further part of the structure.

For each sample, distortion of the fixed plate edge was determined as an arithmetic mean of the difference of the distance between measurement points, determined in the vertical direction (height), before and after butt joint preparation (see Fig. 5). The first measurement was done after application of the mounting (boundary conditions), and the second was performed after removal of the support. The aforementioned height should be understood as the distance between the upper surface of the plate and the base of the support elements (denoted as 2 in Fig. 4). For each sample, the number of measurement points was 16, equally spaced by 100 mm (distances between the first and the last measurement point and the plates' edges were 50 mm each). Distortions were measured using the optical devices in the form of dial indicators providing accuracy equal to 0.01 mm.

The method for calculating the distortion of the fixed plate edge is shown in Fig. 5.

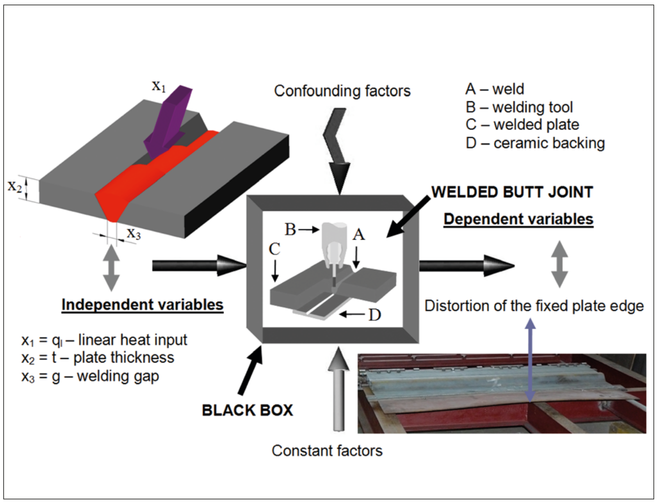

Fig. 3. Black box of designed experiment (according to [27])

Tab. 2. Experiment plan – standardized values (according to [27])

No. of experiment	Linear heat input x_1 (q_l)	Plate thickness x_2 (t)	Welding gap x_3 (g)
1	–1	–1	0
2	+1	–1	0
3	-1	+1	0
4	+1	+1	0
5	–1	0	–1
6	+1	0	–1
7	–1	0	+1
8	+1	0	+1
9	0	–1	–1
10	0	+1	–1
11	0	–1	+1
12	0	+1	+1
13	0	0	0
14	0	0	0
15	0	0	0
Actual values of particular independent variables belong to the following intervals: $q_l \in [1{,}0; 2{,}6]$, kJ/mm, $t \in [6; 10]$, mm, $g \in [4; 8]$, mm.			

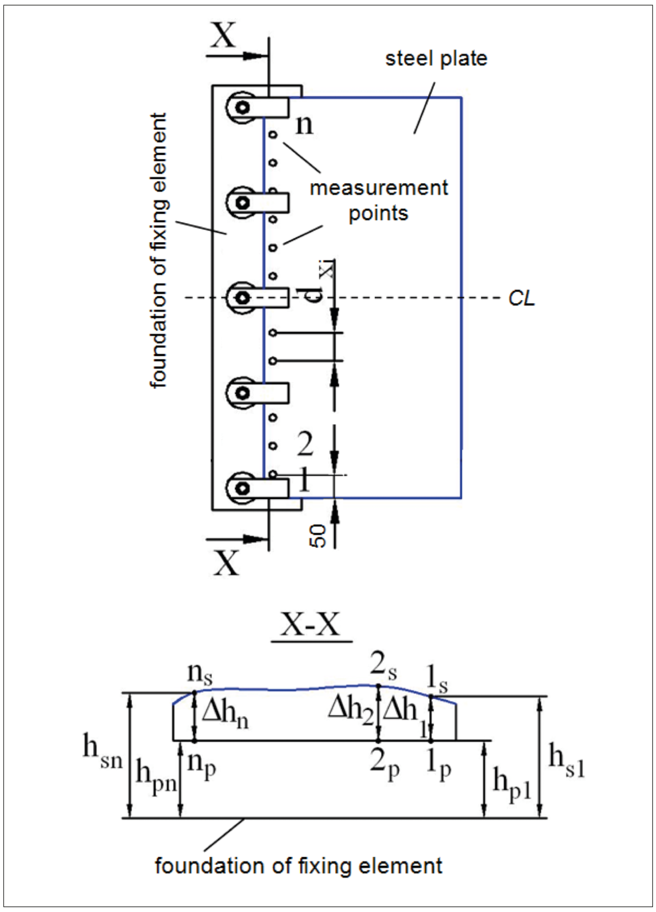

Fig. 5. Method of distortion of the fixed plate edge determination (according to [27])

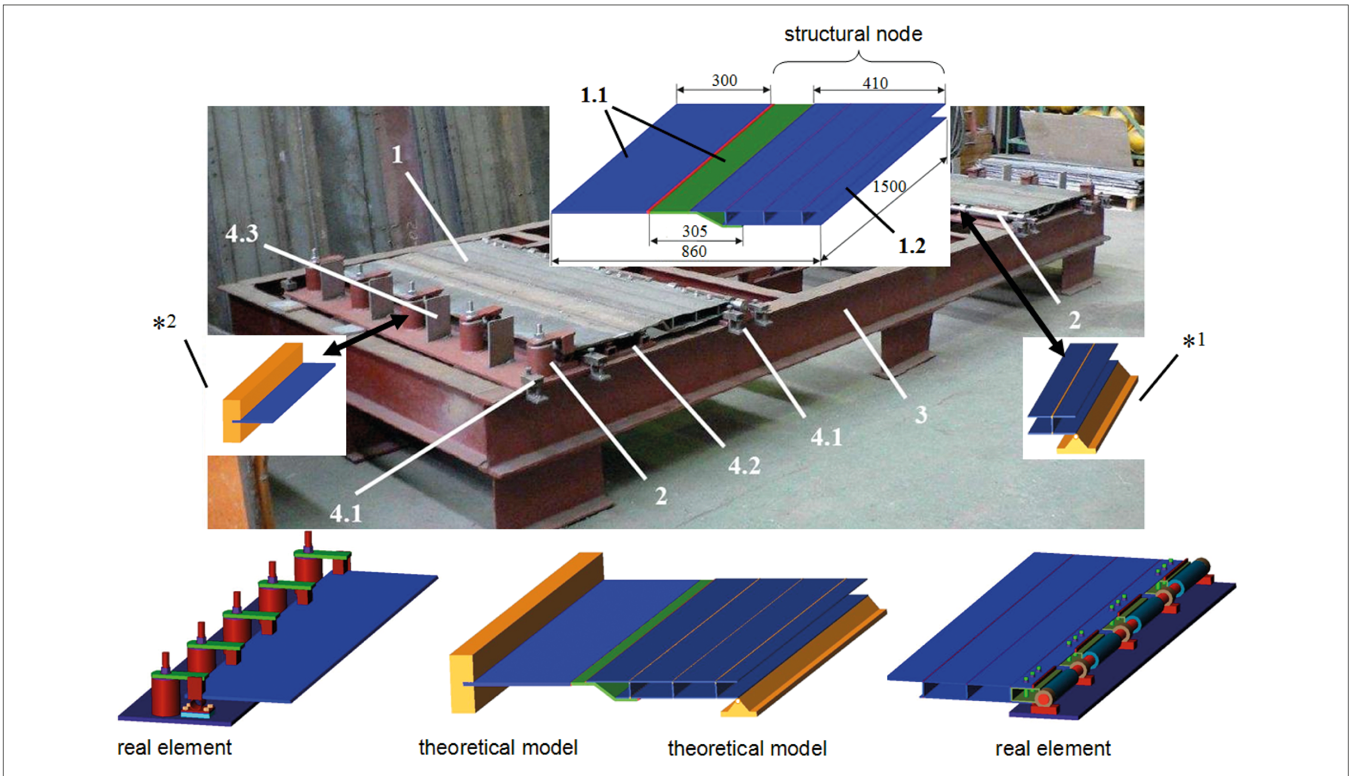

*Fig. 4. Stand with investigated object (according to [27]): 1 – investigated object, 1.1 – steel plates, 1.2 – stiffened panel, 2 – elements of a support (simulating boundary conditions: *1 – clamped support, *2 – fixed), 3 – position base (jig), 4 – additional elements: 4.1 – mounting elements, 4.2 – hold-up elements, 4.3 – auxiliary elements fixing sample position*

$$DFE = \frac{1}{n} \cdot \sum_{i=1}^{n} \Delta h_i \quad (2)$$

$$\Delta h_i = h_{si} - h_{pi} \quad (3)$$

DFE – the measure of distortion of the fixed plate edge
h_i – distances between the measurement points in the vertical direction; $i = 1, \ldots, n$
Δh_i – difference distances between the measurement points in the vertical direction; $i = 1, \ldots, n$
d_{xi} – distances between the measurement points in the longitudinal direction (dxi = 100 mm)
1, 2, …, *n* – numbers of consecutive measurement points ($n = 16$)
bottom indices are: *p* – value before welding; *s* – value after welding; $i = 1, \ldots, n$

RESULTS OF INVESTIGATIONS

The method employed to predict the distortion of the fixed plate edge was based on analysis of the regression models of dependent variables with respect to independent variables. The analysis of regression models is commonly utilised in various scientific research, including experimental studies in the field of welding technology [20, 33, 34]. Processing of the results followed the rules contained in [7, 14, 15], using the STATISTICA software to support statistical analysis.

Particular regression coefficients were determined at the significance level $\alpha = 0.05$ (confidence coefficient 95%).

Evaluation of the results obtained for the analysed distortion form reveals the significance of the three variables selected for the experiment and the interdependence between them.

The polynomial describing the dependence between the analysed weld distortion form and the adopted technological-construction parameters is described by Eq. (4). Table 2 shows the values of the corrected square of the multiple correlation coefficient (Corrected R^2) and F-Snedecor statistics for the investigated distortion form. A summary of the regression and the list of important variables are presented in Table 3.

$$y_{DFE} = -b_0 + b_1 q_l + b_2 t - b_{12} q_l t - b_{22} t^2 \quad (4)$$

where:
y_{DFE} – distortion of fixed plate edge,
$b_0, b_1, \ldots, b_{22}$, – regression coefficients,
q_l, *t* – independent variables selected for the experiment (see Fig. 3 and Table 1).

Four functions were selected for the regression model based on the calculations conducted. Table 2 shows that the calculated value of statistics $F = 26.15$ exceeds the critical value $F_{0.05,4,10} = 3.48$ for four degrees of freedom of a numerator and ten degrees of freedom of a denominator (the critical value was taken from the statistical tables in [14]). Moreover, the *p* value is much smaller than the significance level α.

Table 3 illustrates the results of detailed statistical analysis only of important variables. The presented analyses confirm that the dependence (4) is statistically significant and can be used to predict the value of the DFE variable as a function of two out of three selected independent variables: linear heat input q_l and plate thickness *t* (welding gap g proved to be insignificant). The obtained values of the corrected square of the multiple correlation coefficient (Table 2 and Table 3) indicate fitting of a regression surface to the experimental data at the level of 88%. This is ultimately confirmed by a plot of the residual of the analysed model (see Fig. 6A). The location of the points on this plot shows that the distribution of residuals in the adopted model does not significantly depart from the normal distribution.

Tab. 2. Comparison of the values of: corrected square of multiple correlation coefficient and F-Snedecor statistics for DFE (according to [27])

Symbol of dependent variable	Value of Corrected R^2	Value of *F*-statistics determined based on regression analysis	Critical value F_{kr}, from statistical tables (for significance level $\alpha = 0.05$)
y_{DFE}	0.87784	$F(4,10) = 26.150$; p<0.00003	$F(4,10) = 3.48$

Tab. 3. Comparison of important variables, obtained using stepwise regression method, for DFE (according to [27])

Summary of dependent variable regression: y_{DFE} $R = 0.95537431$ $R^2 = 0.91274007$ Corrected $R^2 = 0.87783610$ $F(4,10) = 26.150$ $p < 0.00003$ Standard error of estimation: 0.92678						
N=15	Beta	Standard error Beta	B	Standard error B	t(10)	Level p
Free term			−4.79018	8.645741	−0.55405	0.591717
t^2	−2.16635	1.097922	−0.23661	0.119914	−1.97314	0.076743
q_l	1.10470	0.536617	4.84375	2.352884	2.05864	0.066538
q_l*t	−0.99285	0.613440	−0.46875	0.289620	−1.61850	0.136625
t	1.74869	1.137446	3.06696	1.994927	1.53738	0.155216

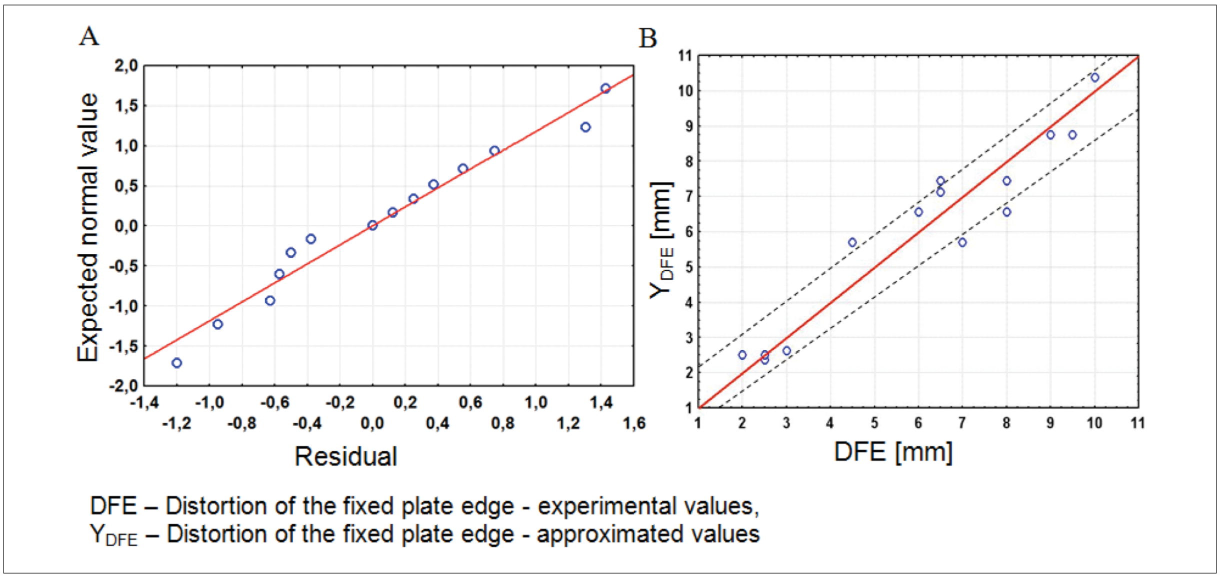

Fig. 6. Evaluation of accuracy of predicted values: A – residual normality plot, B – comparison of experimental values with the ones calculated based on approximation equation (according to [27])

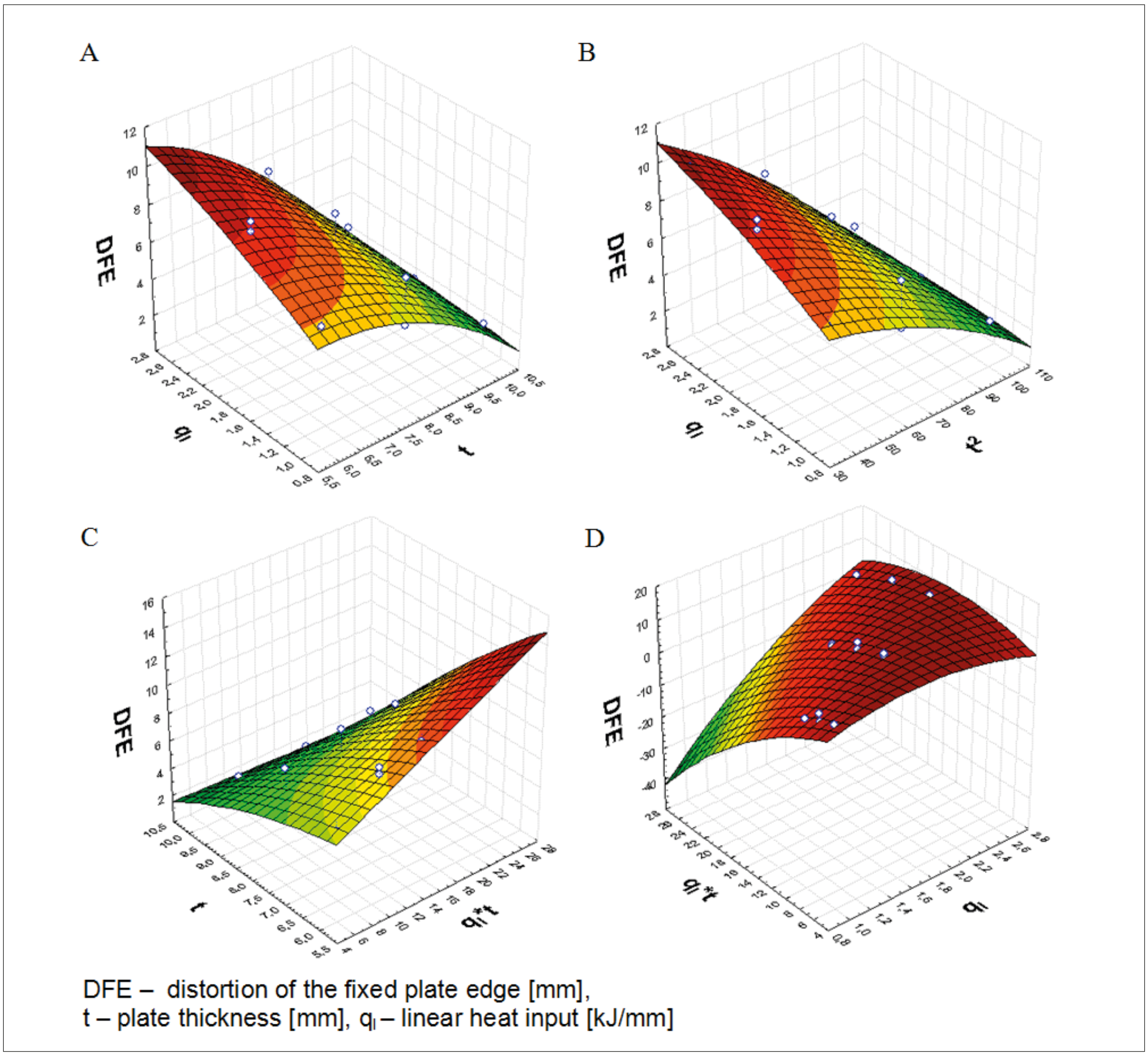

Fig. 7. Influence of technological-construction parameters on distortion of fixed plate edge: A – plate thickness and linear heat input, B – square of plate thickness and linear heat input, C – product of linear heat input/plate thickness and plate thickness, D – linear heat input and product of linear heat input/plate thickness (according to [27])

The accuracy of prediction was evaluated by comparison of the values calculated based on the approximation equation with the experimental values, as depicted in Fig. 6B. The aforementioned values were indicated on the same plot. The values of the independent variables, obtained with both methods, were aligned along a straight line running from the origin of the coordinate system at an angle of 45°, which indicates good conformity between the prediction and the actual situation. (The biggest difference in results for both methods is 1.43 mm, the smallest difference is 0.00 mm, the mean value of difference is 0.64 mm.)

The described interdependences between the technological-construction parameters can be illustrated graphically in the form of three-dimensional plots. Such plots can present only two parameters simultaneously (present separately or in the form of interaction). Fig. 7 shows this type of plot for the selected variables.

The linear heat input of the welding process and plate thickness (Fig. 7A and B) as well as their interaction (Fig. 7C and D) have a very significant impact on the magnitude of distortion of the fixed plate edge. An increase in linear heat input results in a substantial increase in distortion, which is clear in Fig. 7A and B. A similar situation is observed upon an increase in the aforementioned interaction, especially in correlation with the plate thickness (see Fig. 7C). However, the linear heat input in correlation with the interaction of both independent variables has a smaller effect on the magnitude of distortion, which is visible in Fig. 7D.

The importance of the independent variables to the analysed distortion form can also be presented by comparing the measurement results for defined arrangements of the designed experiment, which is presented in Fig. 8 based on the example of plate thickness. This figure compares the experimental arrangements having an identical level of linear heat input (mean level) and all levels of the plate thickness parameter, namely: Fig. 8A – the maximum level, Fig. 8B – the minimum level and Fig. 8C – a medium level. It can be seen that the maximum distortions occur for the minimum plate thickness (Fig. 8B) and the minimum distortions are associated with the maximum plate thickness (Fig. 8A). This confirms actual situations observed in industry.

The approximation equation, obtained as a result of the designed experiment, allows technological evaluation of the structure section by means of simulations conducted using a prediction equation based on significant parameters (the independent variables). Such simulations were presented in [28]. The performed analyses show that proper selection of significant parameters makes it possible to influence the magnitude of weld distortions and thus to determine the quality of pre-fabricated fragments of steel structures.

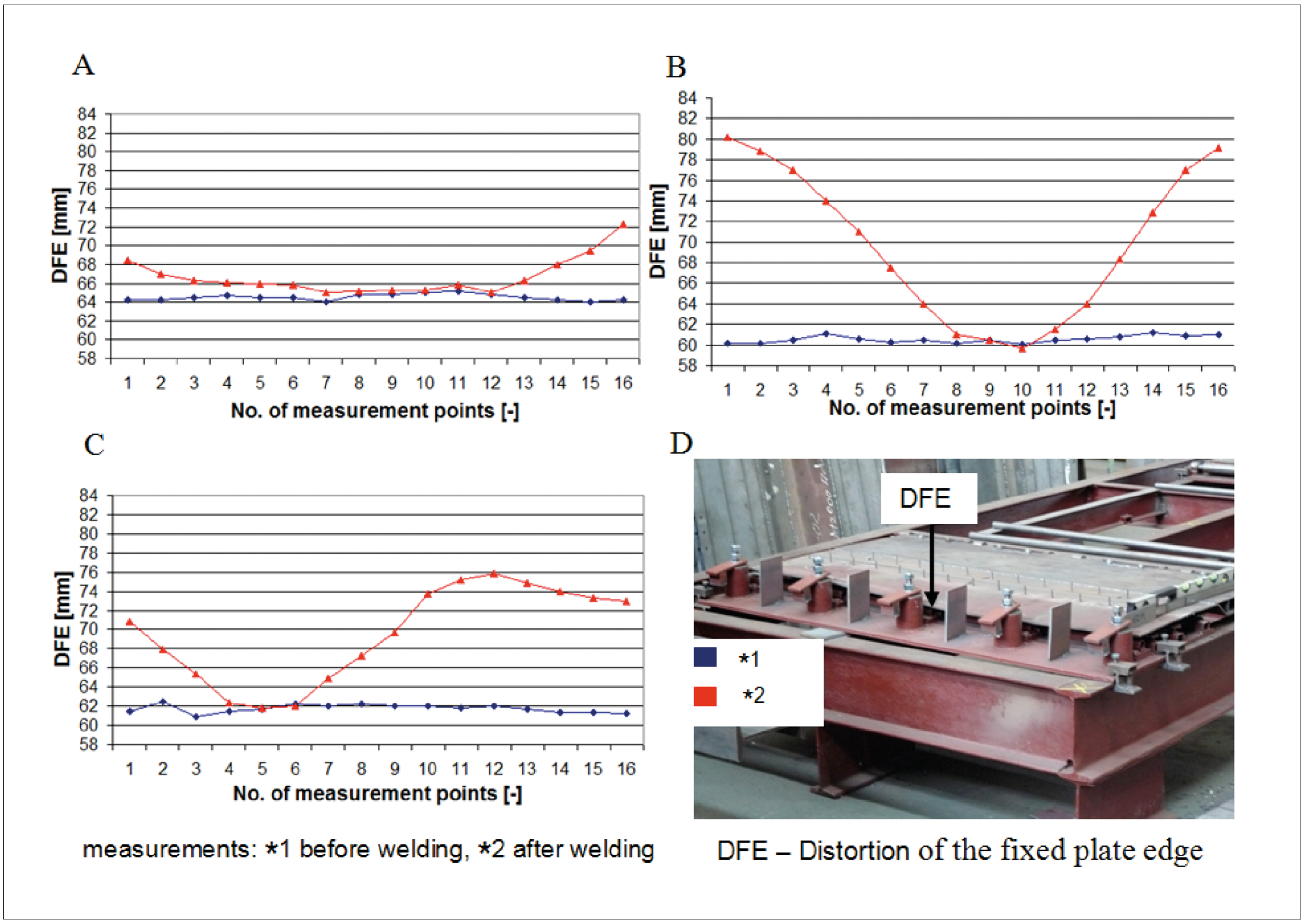

Fig. 8. Magnitude of distortion of fixed plate edge for particular experiment arrangements: A – no. 12, B and D – no. 9, C – no. 14 (according to [27])

CONCLUSIONS

The paper shows that evaluation of the designed experiment results allows the elaboration of a mathematical model to predict distortion of the fixed plate edge. Such evaluation makes it possible to describe the technological-construction parameters that are relevant to the magnitude of the analysed form of weld distortion. The paper proves the good accuracy of the prediction. Moreover, it was revealed that the most important impact on the fixed plate edge originated from two independent variables selected for the experiment, namely the linear heat input of the welding process and the plate thickness. When applying the prediction model, one has to remember two very important aspects. First of all, the condition that must be fulfilled during the prediction based on the approximation polynomial is the fact that the technological-construction parameters used must belong to the defined space of the executed experiment plan. Secondly, one cannot expect a result of similar quality in every case, because the magnitude of the technological parameters has a probabilistic character, which can result in bigger differences between the prediction and the actual state.

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