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Research Article

ANALYSIS OF ASSEMBLY SUITABILITY OF THE HYBRID NODE BASED ON WELD DISTORTION PREDICTION MODELS

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ABSTRACT
The article presents an analysis of assembly suitability of the innovative hybrid node. Weld distortions are a factor that affects significantly the quality of a structure during its pre-fabrication stage, thus increasing manufacturing costs . For the purposes of this analysis, such distortion forms were chosen that are the highest-ranking ones in the technological hierarchy. The analysis was performed taking advantage of significant parameters in order to demonstrate the possibilities of using mathematical models determined on the basis of a designed experiment to modify the construction technology as early as during the stage of the hybrid node's manufacture. It was shown that using the above-mentioned theoretical models a technological assessment of the structural component can be performed by selecting such system of parameters that will produce distortions at a level acceptable from the point of view of further assembly suitability.

Keywords: innovative structural component, sandwich panel, hybrid node, weld distortions, prediction models.

INTRODUCTION

This article continues the subject of assembly suitability of hybrid nodes. The author's previous article on the effect of particular forms of hybrid node weld distortions on the node's assembly suitability was published (see [12]).

In order to remove any ambiguity regarding the concepts discussed herein, the following terms are recalled or introduced:

- hybrid node – a special fragment of a large-size steel structure within which two parts (distinguished from each other in structural and technological terms) of that structure are joined (in the case analyzed – see Figure 1: an I-core sandwich panel and a conventionally stiffened plate). The two fragments of the structure are joined with each other using an intermediate element – a connector [9, 11],
- assembly suitability – the structure's (or its fragment's) ability to be joined with another structure, or a fragment thereof, preferably without the need for any further corrective procedures [9, 10].
- significant parameters – purposefully selected quantities responsible for the formation of weld distortions (identical to the independent variables of the designed experiment).

Weld distortions are the most unwelcomed phenomena affecting the quality of welded components. They are to blame for significant worsening of the assembly suitability of prefabricated technological subcomponents in all types of large-size steel structures. The flat section (i.e. the stiffened-plate) is the fundamental component of most of such structures. Despite their structural simplicity, these sections are characterized by substantial labor intensity related to the technological processes required for their manufacture. A considerable portion of the required outlays (in terms of both labor intensity and material consumption) is consumed by repair works – mainly thermal straightening – aimed at improving the section's poor quality, meaning quality that is unacceptable from the structure execution standards standpoint. The quality with which the flat sections have been manufactured has a large impact on their assembly suitability [5] in later stages of constructing large-size structures, in which minimization of the total assembly time is of importance [2]. Thus, assembly suitability is a measure of the quality of prefabricated welded structures.

Financial outlays on removing weld distortions are considerable and have a negative impact on the competitiveness of production plants, particularly those that manufacture large-size steel structures. That is why, developing distortion prediction models and using them in order to modify the technological construction processes is an important factor contributing to the improvement of assembly suitability.

In papers [9] and [12] several weld distortion forms were identified which can occur within the hybrid node. Also, the effects of each of them on assembly suitability were presented.

Taking the broad scope of the subject discussed into consideration, as well as the limits concerning this paper's size, the analysis was only run for those distortion forms that occupy the highest positions in the hybrid node's technological hierarchy – namely those that have the greatest impact on its assembly suitability. Those distortion forms are (based on [12]): Longitudinal distortion – deflection – of the panel plate at weld no. 1 (DWP1), Longitudinal distortion – deflection – of the panel plate at weld no. 2 (DWP2), transverse shrinkage at butt weld (SP3), angular distortion of the connector at weld no. 2 (DKL2). The numbers accompanying distortion symbols refer to the hybrid node's weld numbers (Fig. 1).

WELD DISTORTION PREDICTION MODELS

Weld distortion prediction models for hybrid nodes were obtained through experimental research performed in accordance with the rules of experimental design technique. In line with those rules, the joint being welded was examined as the so-called black box. On input, the earlier purposefully selected parameters responsible for the formation of distortions (these parameters are referred to as independent variables) were introduced. On output from the black box, responses to those parameters (the so-called dependent variables) were recorded. There are also two more groups of quantities related to the black box, and these are the so-called confounders and constant factors. However, as they are neither (overtly) controllable nor measurable they were deemed to be of little relevance. For the purpose of analyzing the hybrid node's weld distortions, three independent variables were selected. Depending on the node's weld, one of them varied (Fig. 1). The

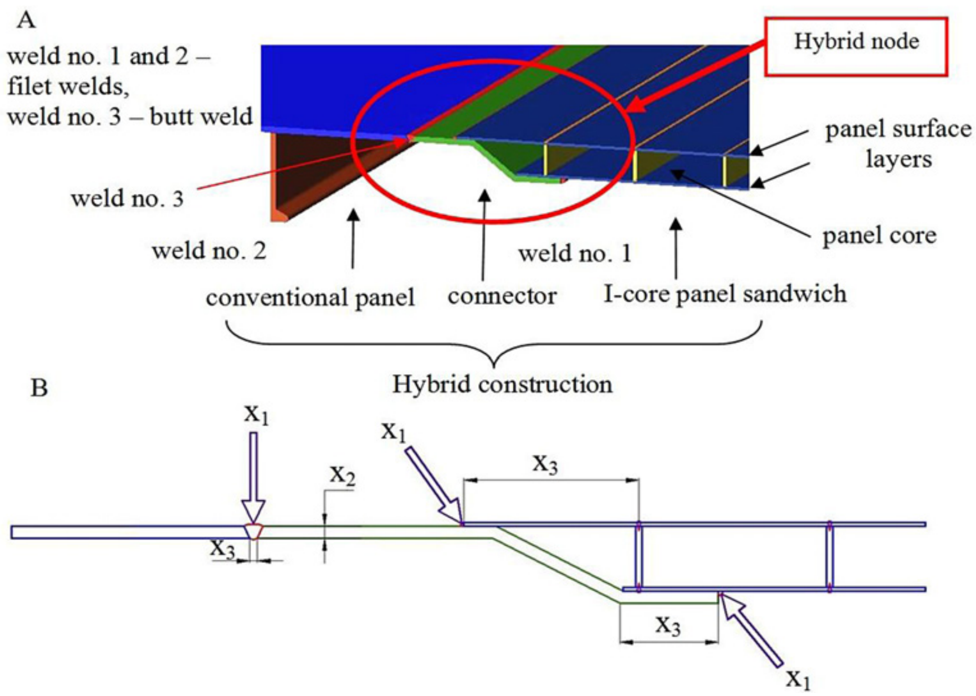


Fig. 1. Hybrid node: A – components, B – independent variables: x_1, x_2, x_3 (on the basis of: [9])

input quantities that did not vary (for each of the welds) were: the heat input of the welding process (x_1) and the connector's thickness (x_2). The third of the variables (x_3) was: the width of the bottom side of the connector (for weld no. 1), the width of the fragment of the panel's upper plate (for weld no. 2) or the root gap (for weld no. 3). The above-described black box of the designed experiment illustrating the independent variables selected for the transverse shrinkage at the butt weld is shown in Figure 2.

The experiments were performed on the basis of the 3(K-p) Box-Behnken design (e.g.: [4, 8]), in which the input values were changed on three levels (i.e. minimum, medium and maximum levels). There were 15 experiments in one (required) block (depending on the volume of data possessed, this block of 15 experiments can be run multiple times). With regard to the scope of their parameters, the minimum, medium and maximum values of the independent variables corresponded to the scope of the structural and technological parameters used under production conditions (See Table 1).

When assessing the results, it was decided which of the assumed independent variables were significant parameters. Subsequently, it was investigated which of the approximation functions was adequate to the observed results.

Quadratic polynomial with first-order interactions of a form illustrated by the dependence depicted in (1) was assumed as the approximated function of the studied object. A list of regression equations describing the analyzed forms of hybrid node weld distortions is shown in Table 1.

$$y_i = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 \quad (1)$$

where: y_i – dependent variable being determined (the specific form of distortion),
b_0, b_1, ..., b_{33} – regression coefficients,
x_1, x_2, x_3 – independent variables selected for the experiment (see Fig. 1).

On the basis of the available literature sources concerned with analyses of the results of experimental research (e.g.: [1, 3, 6, 7]), an assessment of the values obtained for the weld distortion forms studied allows for the conclusion that all the independent variables and the interdependences between them are significant.

In the Pareto charts (sample charts – for DWP1 and SP3 – are shown in Figure 3), the effects of particular independent variables and their interactions on the weld distortion form analyzed are shown. In these charts, the vertical broken line denotes the critical value for a t-test assessment of the significance of a given factor's effect on the dependent variable.

The approximation polynomials presented in Table 1 are the prediction models sought

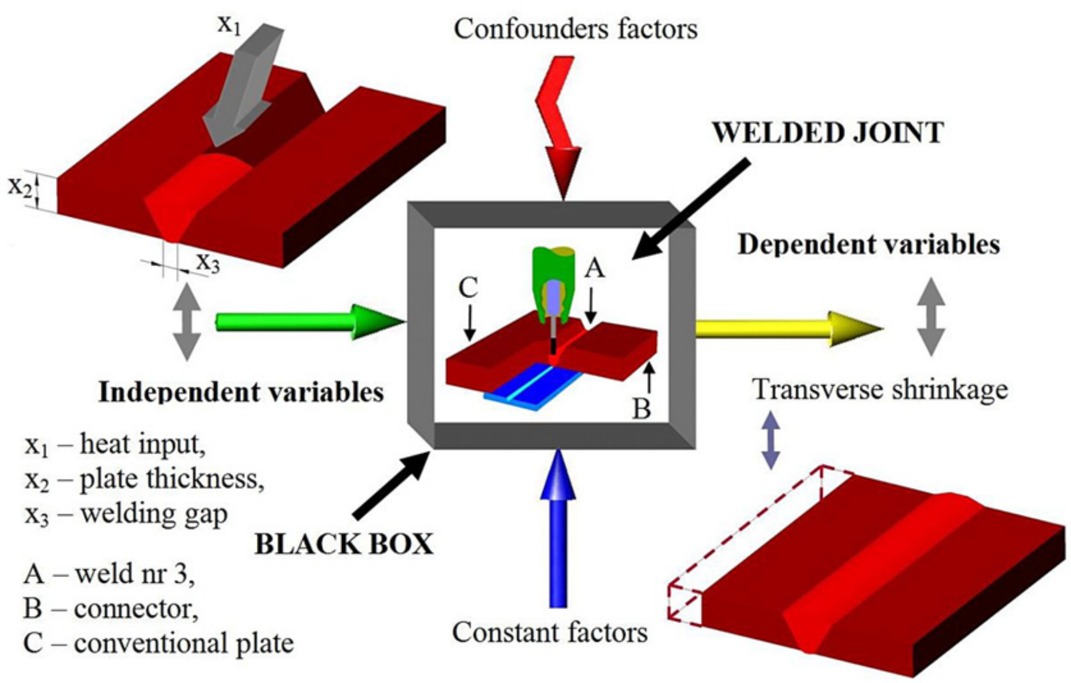


Fig. 2. Black box of the experimental design

Table 1. List of regression equations approximating the types of weld distortions (on the basis on [9])

No	Distortion form symbol	Form of regression equation	
1	DWP1	$y_{DWP1} = b_0 - b_3x_3 - b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3$	(2)
2	DWP2	$y_{DWP2} = b_0 - b_3x_3 - b_{12}x_lx_2 + b_{13}x_1x_3$	(3)
3	SP3	$y_{SP3} = -b_0 + b_2x_2 + b_{13}x_1x_3 - b_{22}x_2^{\ 2}$	(4)
4	DKL2	$y_{DKL2} = b_0 - b_2x_2 - b_3x_3 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{33}x_3^{\ 2}$	(5)

Denotations:
$b_0, b_1, ..., b_{33}$ – regression coefficient,
x_1, x_2, x_3 – independent variables selected for the experiment (see Fig. 1) whose actual values ranged between:
$x_1 \in [0.4;2.0]$, $x_2 \in [6;10]$, $x_3 \in [45;75]$ for weld no. 1, $x_3 \in [60.110]$ for weld no. 2, $x_3 \in [4.8]$ for weld no. 3
The range of variability of particular independent variables is presented using the following units:
$x_1 \in$ [kJ/mm], $x_2 \in$ [mm], $x_3 \in$ [mm] for all welds.

on the basis of which the value of the given distortion form can be forecast for any chosen combination of independent variables. The only condition that must be met while making such forecasts is that the significant parameters should belong to the definition space of the experimental design.

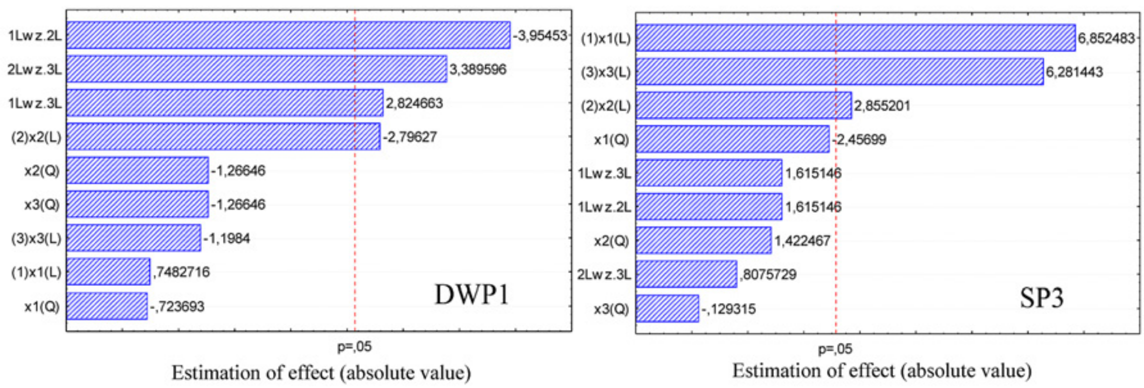
ANALYSIS OF ASSEMBLY SUITABILITY OF THE HYBRID NODES

The purpose of this analysis is to show the possibilities of using prediction models in order to modify the construction technology during the stage of hybrid node prefabrication.

The analysis was performed on the basis of simulations using prognostic equations determined by the author (see Table 1), based on significant parameters. An identical complex set of significant parameters (independent variables) was selected for the analysis of each distortion form simulated, in which:

- two parameters were characterized by variability ranges reaching levels used during the designed experiment, i.e. minimum (min), medium (med) and maximum (max). x_1, x_3 were selected to this group. These parameters were named directional parameters.
- one parameter was characterized by a variability range that fitted within the experimental levels of variability, but that has additional values increasing the simulation's informational value. As this parameter is the element's thickness (x_2) it was assumed that it varied every 1 mm. This parameter was named the decisive parameter.

Each set of significant parameters constitutes a separate structural and technological variant (Table 2) which can be used under the hybrid node manufacturing conditions. Simulation results are shown in Figure 4.



Denotations of the independent variables and their effects					
in charts	in polynomial	in charts	in polynomial	in charts	in polynomial
(1)x1(L)	x_1	1Lwz.2L	$x_1\ x_2$	x1(Q)	x_1^2
(2)x2(L)	x_2	1Lwz.3L	$x_1\ x_3$	x2(Q)	x_2^2
(3)x3(L)	x_3	2Lwz.3L	$x_2\ x_3$	x3(Q)	x_3^2

Fig. 3. Pareto chart of effects for SP3 (on the basis of [9])

Table 2. Structural and technological variants of significant parameters [9]

k-t variant no. *1	Significant parameters set *2			k-t variant no. *1	Significant parameters set *2			k-t variant no. *1	Significant parameters set *2		
	x_1	x_2	x_3		x_1	x_2	x_3		x_1	x_2	x_3
1	min	6	min	16	med	6	min	31	max	6	min
2	min	7	min	17	med	7	min	32	max	7	min
3	min	8	min	18	med	8	min	33	max	8	min
4	min	9	min	19	med	9	min	34	max	9	min
5	min	10	min	20	med	10	min	35	max	10	min
6	min	6	med	21	med	6	med	36	max	6	med
7	min	7	med	22	med	7	med	37	max	7	med
8	min	8	med	23	med	8	med	38	max	8	med
9	min	9	med	24	med	9	med	39	max	9	med
10	min	10	med	25	med	10	med	40	max	10	med
11	min	6	max	26	med	6	max	41	max	6	max
12	min	7	max	27	med	7	max	42	max	7	max
13	min	8	max	28	med	8	max	43	max	8	max
14	min	9	max	29	med	9	max	44	max	9	max
15	min	10	max	30	med	10	max	45	max	10	max

*1 – structural and technological variant,
*2 – assumed set of independent variables (x1 – welding heat input, x2 – connector thickness, x3 – depending on the hybrid node joint: the width of the bottom side of the connector or the width of the fragment of the panel's upper plate or the root gap).

In order to arrive at a fuller assessment, the simulation results were divided into three ranges for each distortion form (Table 3). These simulation results show (Fig. 4, Table 3) that:

- the set of significant parameters has a distinct effect on the value of the distortion,
- for each distortion form, over half of all the results obtained are within the medium range of values,
- depending on the distortion form, different sets of parameters determine the extreme distortion values (Table 4). In every case, adequate levels of welding heat input correspond to the minimum and maximum distortion levels. As for the remaining parameters, this rule does not apply.

Any of the independent variables (of different variability ranges) can be the decisive parameter. For the purpose of comparing the effects of the applied decisive parameters with the distortion value, it was decided that additional calculations should be run for one of the distortion forms. The first distortion form in the technological hierarchy

Table 3. Grouped lists of simulation results [9]

Distortion form symbol	Interval of results	Numerical interval of results	Number of results in the given range	% share of results of the given range in the total number of results*
DWP1	min	0–0.85	7	15.55
	med	0.85–1.7	31	68.90
	max	1.7–2.5	7	15.55
DWP2	min	0–1	16	35.56
	med	1–2	23	51.11
	max	2–3	6	13.33
SP3	min	0–1	1	2.22
	med	1–2	32	71.11
	max	2–3	12	26.67
DKL2	min	0–0.65	6	13.33
	med	0.65–1.3	27	60.00
	max	1.3–2	12	26.67

* total number of results (simulations) for each distortion form was 45.

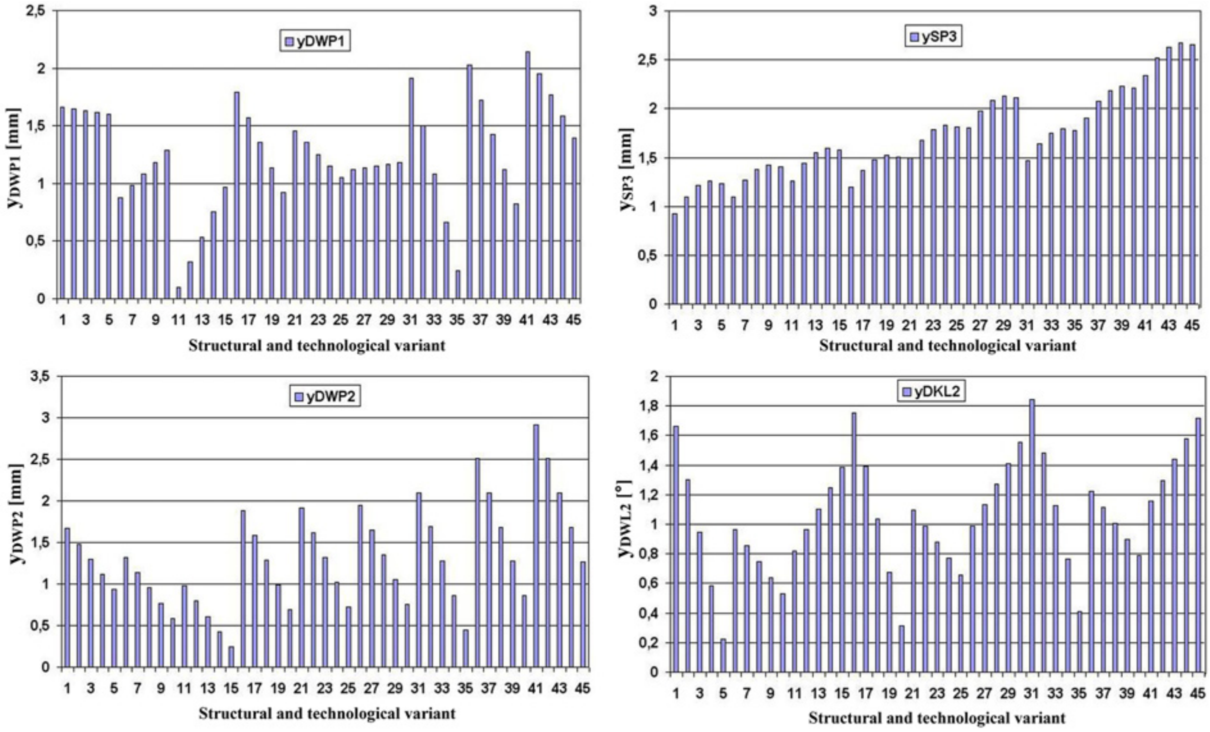


Fig. 4. Forecasting the values of hybrid node weld distortions analyzed (DWP1, DWP2), based on selected structural and technological variants (on the basis of [9]

Table 4. Sets of significant parameters allowing for extreme distortion values to be obtained [9]

Symbol of distortion form	Distortion level	Distortion value [mm] or [°]	Significant parameters set according to Table 2		
			x_1	x_2	x_3
DWP1	min	0.0994	min	6	max
	max	2.141	max	6	max
DWP2	min	0.243	min	10	max
	max	2.919	max	6	max
SP3	min	0.926	min	6	min
	max	2.671	max	9	max
DKL2	min	0.225	min	10	min
	max	1.843	max	6	min

was selected: DWP1. Additional sets of structural and technological variants contained the following parameter distribution:

- directional parameters: x_2, x_3, decisive parameter: x_1. Variability range of the decisive parameter: every 0.10 kJ/mm,
- directional parameters: x_1, x_2, decisive parameter: x_3. Variability range of the decisive parameter: every 5 mm,

The results of the additional simulations are presented in Table 5 and in Figure 5 (as different decisive parameters with different variability ranges were used, the numbers of the obtained structural and technological variants illustrated in Figure 5 were different for each of the two cases).

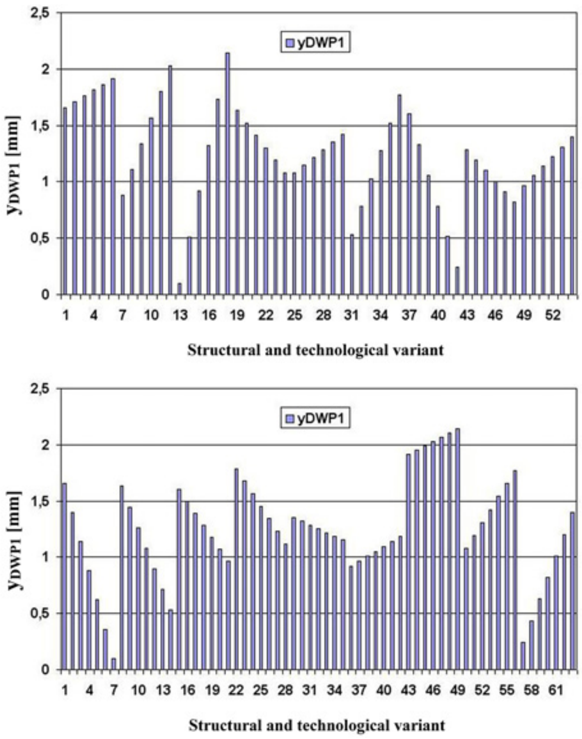


Fig. 5. Summary of the radar chart area values describing the status of the assembly suitability of the hybrid node weld distortion forms assessed (on the basis of [9])

A comparison of the simulation results for DWP1 presented in Figure 4 with the additional simulation results presented in Figure 5 and Table 5 showed that:

Table 5. Grouped lists of DWP1 simulation results for different decisive variables [9]

Decisive variable	Interval of results	Numerical interval of results	Number of results in the given range	Total number of results	% share of results of the given range in the total number of results
Heat input (x_1)	min	0÷0.85	8	54	14.81
	med	0.85÷1.7	36		66.67
	max	1.7÷2.5	10		18.52
Connector thickness (x_2)	min	0÷0.85	7	45	15.55
	med	0.85÷1.7	31		68.90
	max	1.7÷2.5	7		15.55
Width of the bottom side of the connector (x_3)	min	0÷0.85	9	63	14.29
	med	0.85÷1.7	45		71.42
	max	1.7÷2.5	9		14.29

- depending on the type of the decisive variable (and its variability range), different numbers of simulations can be obtained,
- for all decisive variables, the same sets of significant parameters allow for obtaining minimum and maximum distortion values,
- also, for all decisive variables the percentage shares of the results occupy comparable levels in each interval of results.

The foregoing remarks are very valuable from the practical point of view, as they prove that depending on the production purposes each significant parameter can be controlled without affecting the extreme values of the distortions.

CONCLUSIONS

It is shown in this article that a technological assessment of the hybrid node can be performed using prediction models obtained on the basis of a designed experiment. As our analyses indicate, through a skilled selection of the significant parameters one can control the values of the weld distortions and thus determine the assembly suitability of this innovative structural element. This method for modifying assembly suitability, which is based on an analysis of significant parameters, can be performed for any form of hybrid node distortions for which a prognostic model has been developed.

A complete analysis of the assembly suitability of the hybrid node should also involve a comparison of the values of the distortions determined with the values permissible in the light of the currently required quality assurance system for welded structures. However, in the face of missing standards concerning the quality with which hybrid nodes are manufactured, no such comparison was made herein.

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