Paweł Cegielski, Dariusz Golański, Paweł Kołodziejczak, Andrzej Kolasa, Damian Rochalski, Tadeusz Sarnowski

Advanced Design and Verification of Tracks and Welding Positioners – External Axes of Robots

Abstract: Multiaxial welding positioners and tracks intended for integration with an industrial robot as their external axes should be characterised by specific kinematic structure, the wide range of movements and high rigidity translating into previously assumed positioning repeatability. The above-named requirements are often contradictory to one another, therefore the development of a safe and functional structure requires the application of advanced design and verification methods. The pursuit of the accomplishment of the ultimate solution cannot be solely based on the design engineer's intuition or the lowest price criterion. One of the recognised methods of the verification of CAD models CAD involves the application of FEM-based strength analysis (Finite Element Method). The article presents the effect of research and development works related to the design and industrial implementation of new types of manipulators (external axes of robots) in PPU ZAP Robotyka, Ostrów Wielkopolski.

Keywords: welding positioner, track, external axis of a robot, FEM

Introduction

The design and integration of robotic welding stations involve, among other things, the identification of a relationship between a robot (characterised by a specific operating range and position, e.g. standing, upended) and its external axis, i.e. separate machines controlled by the same system as the robot, primarily positioners (manipulating workpieces being welded) and the transport systems of the robots, usually in the form of line tracks [1, 3, 6].

In addition to specific kinematic structure and the range of movements, external axes to be integrated with an industrial robot should be characterised by high rigidity translating into previously assumed positioning repeatability. The above-named requirements are often contradictory as the wide range of movements or significant lengths of manipulating arms do not favour rigidity and stability. The development and implementation of a well-designed structure poses a significant challenge for the

dr inż. Paweł Cegielski (PhD (DSc) Eng.); dr hab. inż. Dariusz Golański (PhD (DSc) Habilitated Eng.), Professor at Warsaw University of Technology; dr inż. Paweł Kołodziejczak (PhD (DSc) Eng.); prof. dr hab. inż. Andrzej Kolasa (Professor PhD (DSc) Habilitated Eng.); mgr inż. Damian Rochalski (MSc Eng.) – Warsaw University of Technology; Joining Engineering Department; dr inż. Tadeusz Sarnowski, PhD (DSc) Eng. – ZAP Robotyka, Ostrów Wlkp.

design engineer. The pursuit of the accomplishment of the ultimate solution cannot be solely based on the design engineer's intuition or the lowest price criterion.

In relation to increasingly precise industrial robots, characterised by positioning accuracy restricted within the range of ± 0.01 to 0.10 mm, and production processes demanding high stability, it is becoming necessary to provide the highest possible accuracy and rigidity of manipulators (positioners and moving tracks) combined with robots. As regards certain elements, e.g. floor tracks or simple positioners, certain structural or material disadvantages can be compensated by appropriate foundations and fixing to the base. In cases of multi-axial positioners and suspended tracks is it necessary to carefully select all load-bearing elements (beams, arms, outriggers, support columns) and drive-related elements (guide bards, gears, hubs). As regard the reduction of costs and laboriousness, at the stage of industrial tests it is rational to create and analyse CAD structural models as well as to perform related calculations and virtual kinematic tests. The final phase of kinematic tests of physical prototypes entails significant costs, yet it also constitutes the ultimate and objective verification of the quality of adopted solutions. As can be seen, the use of CAD modelling and advanced computing techniques is of great importance as they eliminate the necessity of building actual (and costly) models.

One of the recognised methods enabling the verification of CAD models is the application of the FEM-based (Finite Element Method) strength-related analysis involving the discretisation of a given area by dividing it into a finite number of subareas referred to as elements. Such elements are connected at points known as nodes. The reaction of each element is expressed in the form of a finite number of degrees of freedom characterised by the value of unknown (sought) function in relation to a set of nodal points. The response of the mathematical model is then regarded as approximated by the response of a discrete model obtained through the combination of all of the elements composing the structure subjected to analysis [7, 8].

Test subject and methodology

The research work aimed to assess the behaviour (distribution of stresses and deflection) of selected design variants of L-type and H-type positioners and tracks subjected to static loads. The results presented in the study are concerned with tests performed to develop and implement three new types of manipulators in ZAP Robotyka, Ostrów Wielkopolski [4]. In particular, the tests were concerned with the static verification of ready CAD models performed using the FEM-based strength-related analysis and the LUSAS v.14-7 software programme. The tests involved (Fig. 1):

– L-type positioners (one and two-station positioners, having a load capacity of 250 kg and 500 kg),
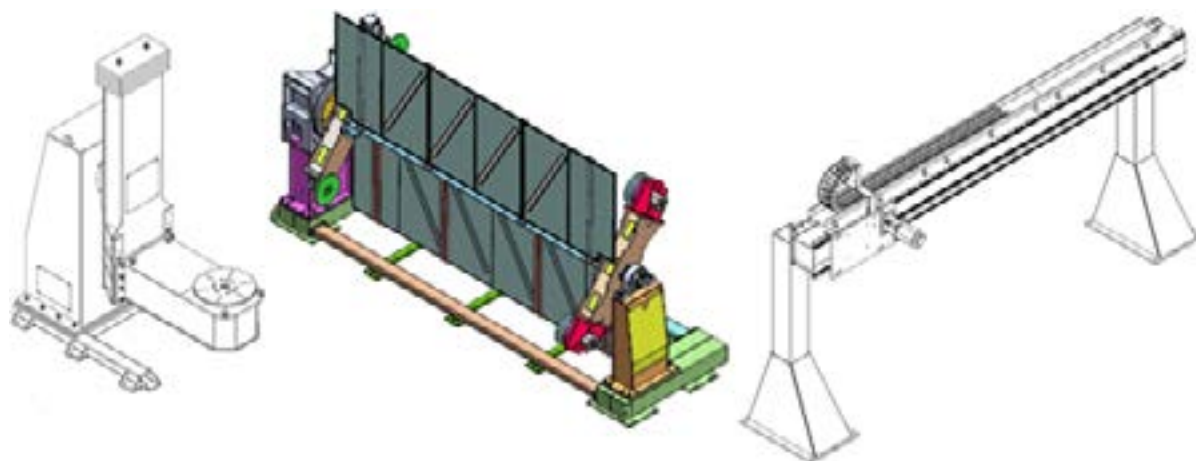

Fig. 1. Designed and tested manipulators (from the left): L-type, b) H-type, c) tracks (selected examples) [2]

- H-type positioners (having a load capacity of 300 kg and 1000 kg),
- module system of tracks in variants presented in Table 1.

The detailed schedule of works, identical in relation to each of the three tasks included the following:

1. Adaptation of CAD structural models to the requirements of the FEM computational models.
2. Identification of the type, nature and range of stresses affecting devices being modelled.
3. Development of basic models for FEM modelling (identification of the type and density of the FEM mesh).
4. Calculations and visualisation of generated deflections and stresses of the CAD models subjected to the tests.
5. Application of conclusions formulated when performing FEM modelling in the verification of the CAD structural models.

The results obtained in the tests were analysed using Huber-von Mises theory in the form of reduced stress, describing the contribution of all of the stress constituents to the effort of the structure. In particular, the high value of reduced stress could indicate the area of the concentration of hazardous stresses possibly leading to the exceeding of the yield point of the material and the formation of permanents strains unacceptable in such structures. The second parameter was vertical displacement (deflection) indicating areas of the excessive deflection of structural elements subjected to a present load.

The calculations involved the structural material from the FEM software database, i.e. steel S355JR. In relation to adopted operating conditions of the models, criteria subjected to assessment were the following:

1. obtainment of forces and bending moments triggering tensile or compressive stresses in the beams, not exceeding the yield point of the structural material, calculated in the area where the elements were fixed to the base,
2. obtainment of elastic strains triggering deflections (deformations) not exceeding 0.05 mm, calculated in the work table area.

Adaptation of CAD models to FEM requirements

Mathematical analyses were performed on the basis of 3D CAD models in the form of STEP files. The initial attempted automatic conversion of the above-named models and their transfer to the FEM programme revealed:

a) uncontrolled movements of certain units of the machine subjected to analysis,
b) incomplete coverage with the FEM mesh etc. (Fig. 2),
c) concentration of the mesh in the areas of lesser relevance, potentially leading to false results (peculiarities),
d) significant extension of computing time in spite of using a high-performance PC.

Similar problems were related to all of the devices subjected to the tests. The reason for such behaviour was the high complexity of the machines, both in terms of their design and kinematic structure (numerous planes, solids, ribs, reinforcements, fixing holes etc.) as well as in relation to the number of components (bolts, nuts, washers, pins, drives, gears etc.). It was necessary to select a method of adapting the 3D

Table 1. Recommended variants of tracks (modules)

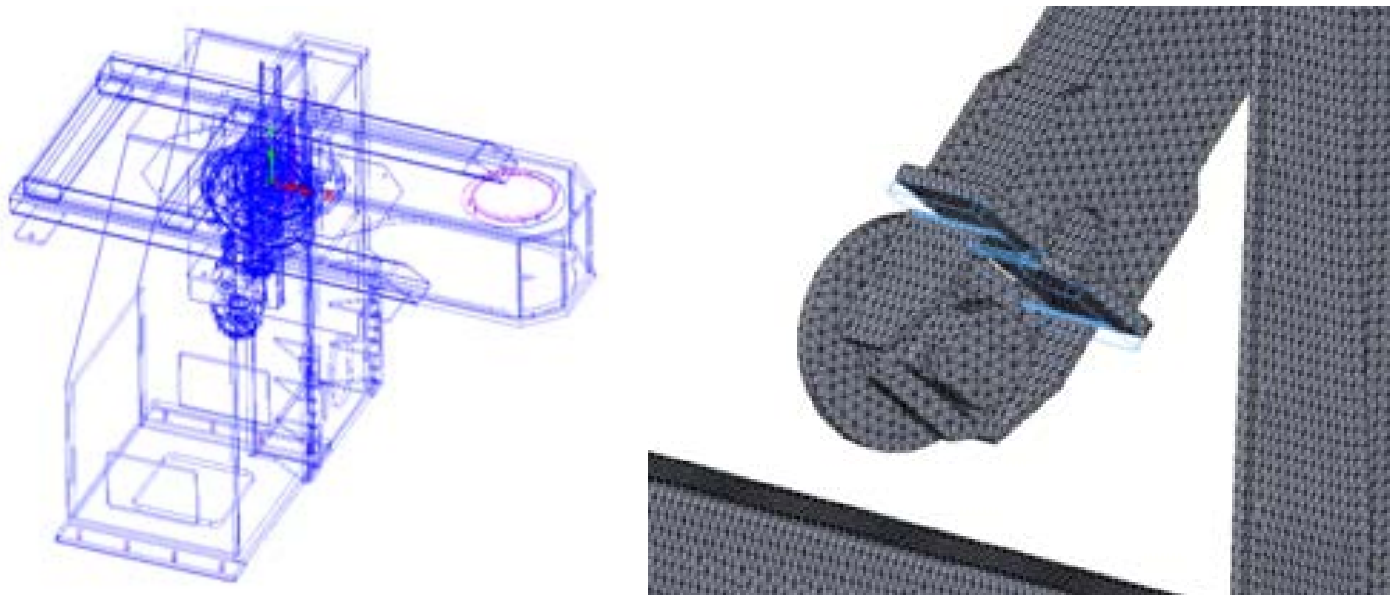| Track (module) length	Robot fixing position and the type of a track (floor or gantry track)	Lifting capacity [kg] and the number of moving platforms		
		250	500	
		1	1	2
2.5 m	Standing (floor track)	yes	yes	-
	On-the-wall (gantry track)	yes	yes	-
	Upended (gantry track)	yes	yes	-
5.0 m	Standing (floor track)	yes	yes	yes
	On-the-wall (gantry track)	yes	yes	yes
	Upended (gantry track)	yes	yes	yes

Fig. 2. Results of unsuccessful conversion of the CAD models to the FEM environment: a) displacement of the elements of the L-type positioner, b) incomplete coverage with mesh in the H-type model

CAD models to FEM modelling-related requirements through:

a) consolidation (clustering) of certain objects (in the figure) by the design engineer, precluding their movements during conversion,

b) removal of certain elements of the figure (making modelling more difficult), yet without losing features which might affect calculations, e.g. small openings,

c) removal of irrelevant parts or components (making modelling more difficult), yet without losing features which might affect calculations, e.g. bolts, nuts, washers etc.,

d) despite using the automatic conversion of data, final models required additional and individual final assessment and manual correction of certain fragments of geometry, which ultimately significantly extended the time necessary for the preparation of the elements for numerical calculations.

A separate issue involved the exclusion of drive-related elements (motor, gear, hub etc.) from the FEM modelling as the above-named components were geometrically complicated and unknown in terms of materials they were made of, yet they constituted significant loads in relation to the machine units subjected to analysis. Finally, the method selected for further tests was the one which involved the determination of the centre of gravity of complete drives (on the basis of provided CAD documentation), where the drives were replaced with simple solids and their weights were entered into calculations on the basis of specifications.

Determination of test loads

It was assumed that the nominal load capacity (lifting capacity) of the devices subjected to the tests was available at the point located in the centre of the work table area (L and H-type positioners) of the moving platform (tracks) and decreased along with the growing distance to the load centre of gravity. The specific design of the L-type positioners was responsible for the fact that the loading of the arms and drives varied significantly in relation to a momentary position of the axis of rotation of the L-arm. Therefore, analysis should involve positions representing various operating conditions (Fig. 3).

In addition, because of the specific operation of the H-type positioners, calculations had to be performed with symmetric loads on both side of the positioner, which reflected the normal operation and operation with unsymmetrical load, i.e. only on one side, which corresponded to loading and unloading.
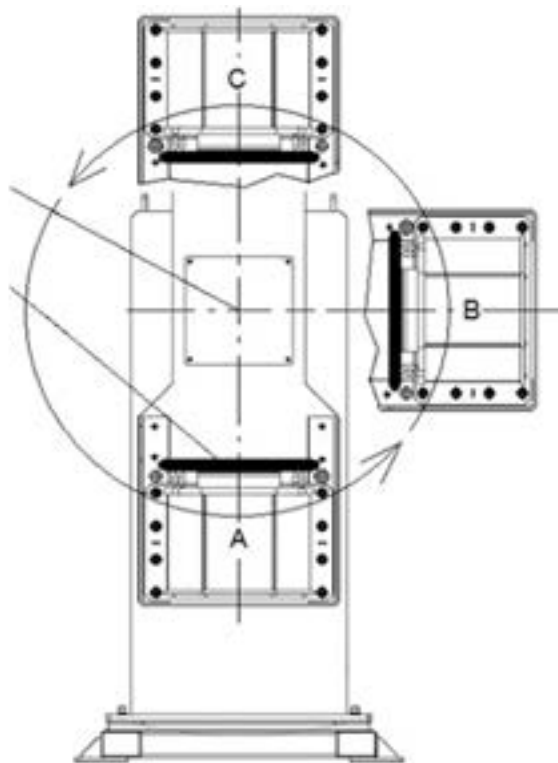
Fig. 3. Analysed positions of the axis of rotation of the L-arm [2]

Because of the specific operation of the tracks, calculations were performed for the following, primary, cases (design variants are presented in Table 1):

1. with the moving platform of the robot in the positioned centrally on the horizontal beam,
2. in relation to variants with two platforms pushed near each other in the middle of the track,
3. floor track and gantry tracks (along with supports),
4. gantry version with upended and on-the-wall position of the robot.

Development of FEM base models

Because of the significant geometrical complexity of the machines subjected to the tests it was necessary to perform initial modelling aimed to identify the appropriate number of finite elements making up a space mesh indispensable for the performance of necessary calculations. This objective involved the creation of a number of identical models, in which the mesh was gradually concentrated by increasing the total number of finite elements. For each variant,

calculations were performed in relation to a specific preset load, where recorded values were the maximum values of deflection (displacement) in the area subjected to the load as well as the maximum values of reduced stress in the entire structure.

It was observed that, in accordance with practice and experience, an increase in the number of the finite elements of a model above a certain value led to a very small increase in the deflection. In turn, reduced stress stabilised in relation to a specific number of elements and started to increase along with a growing number of elements. The FEM-based modelling is often accompanied by the convergence of one parameter (in the case under discussion – displacement) and the divergence or the second parameter (stress). The foregoing is usually ascribed to the peculiarities often occurring in FEM models.

The study concerning the L-type positioners involved the creation of a series of identical models subjected to a load of 250 kg. In the aforesaid models the mesh was gradually concentrated by increasing the total number of elements from approximately 28000 to nearly 800000. The tests involved the recording of the maximum values of the vertical deflection (displacement) of the transverse beam in the area subjected to a load and the maximum values of reduced stress in the positioner structure (Table 2). To maintain compromise between the

Table 2. Effect of the number of finite elements on the value of the maximum vertical deflection and reduced stress in the L-type positioner model [2]

Number of finite elements	Vertical displacement (mm)	Reduced stress (MPa)
28313	0.944	20.46
37169	1.023	23.15
53020	1.086	22.15
90299	1.140	29.79
128979	1.170	31.35
206612	1.190	31.17
441438	1.220	41.15
799226	1.230	44.83

number of finite elements and identified values, further calculations involved the model containing 128979 finite elements, in relation to which the value of vertical deflection did not differ significantly from values related to models containing greater numbers of finite elements [2].

FEM-based analysis of L-type positioners

In cases of the most kinematically complicated L-type positioners it was possible to notice concentrations of stresses in the area of the axis of rotation of the L-arm and certain arms fixing the housing to the base. Figure 4 presents selected results calculated without taking into consideration the weight of the drives and gears (initial tests).

The maximum values of stresses were concentrated in the area of the connection of the vertical beam with the housing and reached approximately 31 MPa in relation to the model subjected to a load of 250 kg (Fig. 4a) and 109 MPa in relation to the model subjected to a load of 500 kg. The model having a capacity of 500 kg, with the arm rotated by 180° (Fig. 4b), did not reveal any special differences as
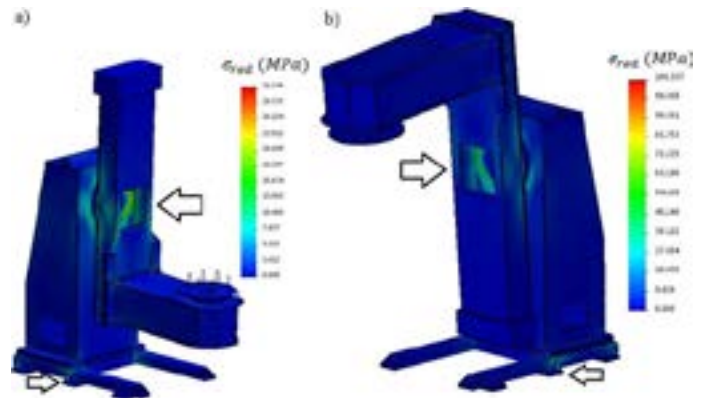

Fig. 4. Distributions of reduced stresses in the L-type positioner models calculated using the FEM: a) subjected to a load of 250 kg, b) subjected to a load of 500 kg, with the arm rotated by 180°

regards the distribution of reduced stresses, mostly amounting to 108.4 MPa. In relation to the arm rotated by 90O (Fig. 3, B), because of the additional twisting of the longer horizontal arm, reduced stress rose to 138.7 MPa. However, the yield point set at 275 MPa was not exceeded in any case.

A problem which emerged when testing the L-type positioner was the vertical deflection measured on the surface of the work table. However, the analysis revealed that the part of the positioner forming the letter "L" was rigid enough not to undergo deflection (an angle of 90° between the arms on the x-y system was maintained) but only to rotate by a certain angle in relation to the horizontal axis, i.e. where the L-arm was connected with the positioner housing (Fig. 5 and 6).
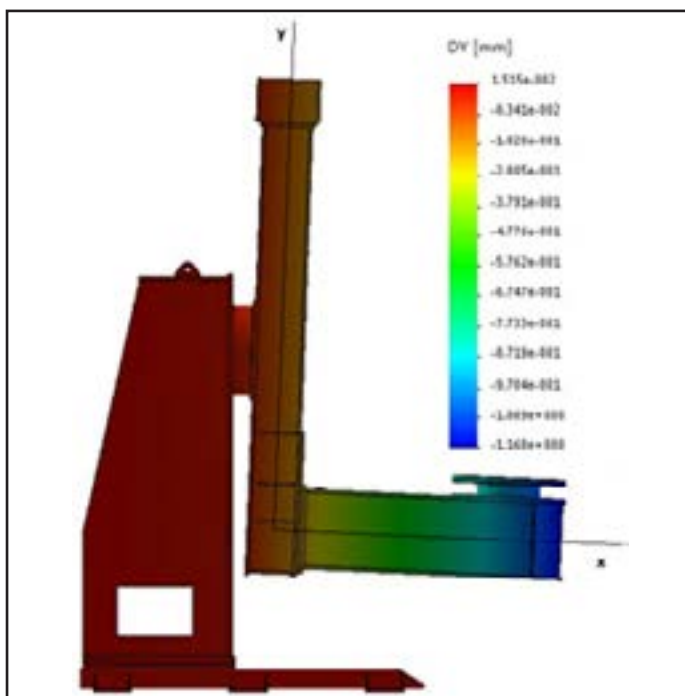

Fig. 5. Vertical displacement (deflection) DY in the L-type positioner (250 kg)
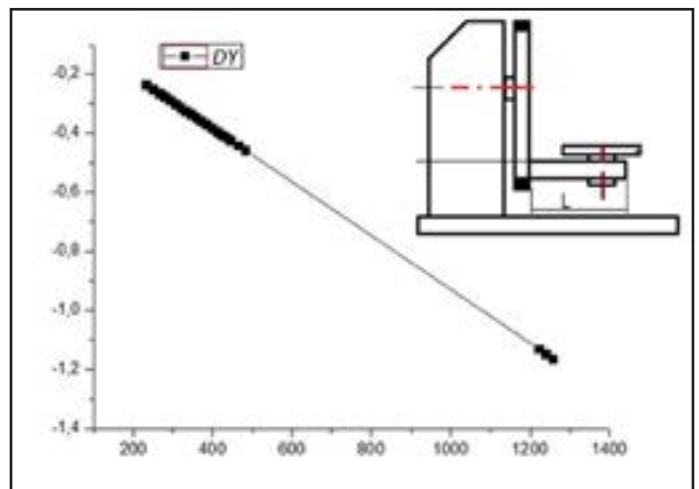

Fig. 6. Change in vertical displacement DY in the function of distance L in the direction of the work table in relation to the L-type positioner (250 kg)
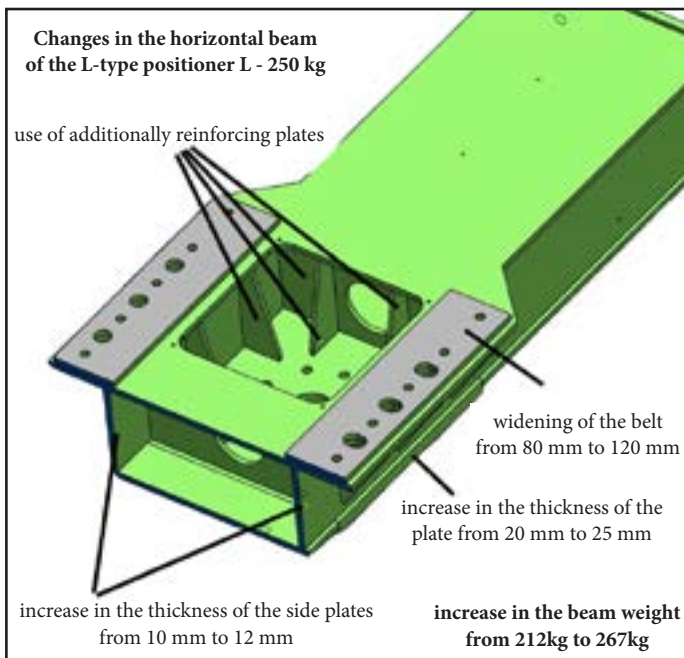
Fig. 7. Reinforcement of the beam illustrated with the an example of the L-type positioner (250 kg)

As can be seen, as regards the L-type positioners, the key area was the connection of the L-arm of the positioner with the housing, i.e. the area of the rotation of the vertical beam in relation to the horizontal axis of the tube connecting the housing with the vertical beam. The tests led to a series of suggested modifications aimed to stiffen the critical joint. Among other things the aforesaid modification included the plugging of the inspection and fixing hole in the beam of the L-arm (modification was rejected because of fixing-related aspects), the increasing of the intermediate plate in the housing in the axis of rotation of the arm as well as providing the L-beam with additional reinforcement (Fig. 7).

The subsequent part of assessment included the investigation of the behaviour of the L-arm in relation to the L250 and L500 positioners in a situation, where the vertical arm of the positioner was stiffened on the entire area (not affected by the unknown element, i.e. the commercial axle of the drive system). Figure 8 presents distributions of reduced stress and vertical deflection in relation to the rigid fixing of the vertical positioner arm, where the disc of the positioner was subjected to a load of 250 kg.

The maximum values of reduced stress proved very low and the vertical deflection at the end of the horizontal arm reached its maximum value DY = -0.06 mm. Such a result indicated and confirmed that the key area in the positioner design was the connection of the drive elements with the housing and the vertical arm of the positioner. In practice, it was not possible to control the deflection in the positioner drive system elements. The designed structure of the positioner seemed to satisfy criteria related to the adopted values of allowed deviation on the work table surface. The foregoing also indicated that designed structural elements of the L-type positioner arms were selected properly. In the central area of the disc of the horizontal arm of the positioner the deflection did not exceed the assumed value amounting to 0.05 mm.
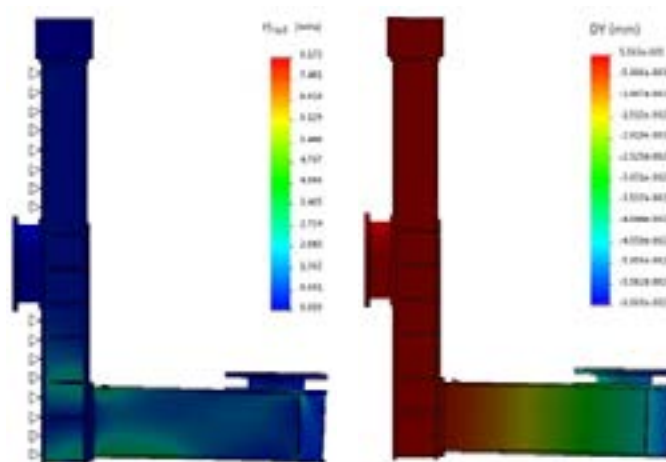

Fig. 8. Arms of the L-type positioner (250 kg) with fixing on the vertical part of the arm: a) distribution of stresses, b) distribution of vertical deflection

FEM-based analysis of H-type positioners

The H-type positioners were analysed in relation to the analysed design variants subjected to a load of 300 kg and 1000 kg. The primary position of the H-positioner was the one in which the arms (rotating beams) with the discs were at an angle of 36° in relation to the vertical axis. The adopted computational variants assumed the extension of strength-related analysis to

include cases where rotating beams were positioned horizontally (inclination angle of 90°) as well as in relation to the initial variant (inclination angle of 36°), i.e. when only one side of the positioner was loaded (e.g. during loading).

Similar to the L-type positioners, the yield point of the material was not exceeded. The key issue, in terms of positioning accuracy, proved to the satisfaction of allowed deformation criteria, i.e. the vertical deflection in the centre of the discs, to which elements (to be welded) would be fixed.

In relation to the positioner subjected to a two-sided load of 300 kg with the angular (skew – normal) positon of both arms with the discs, the vertical deflections identified on the surface of the fixing discs were restricted within the range of -0.0377 mm to -0.0521 mm (Fig. 9), where the maximum defection of the horizontal beam of the positioner was DY = -0.152 mm. Slightly higher deflection values were observed on the right side of the positioner, i.e. the one where the arms with the discs were fixed to the smaller housing (without the drive). The foregoing resulted in the recommendation to use the support in the housing without the drive similar to the one with the drive (but without the motor).

When the arms of the discs were in the horizontal position (i.e. momentary position not subjected to assessment), the analogous deflection values were restricted within the range of -0.0767 do -0.0885 mm, where the maximum defection of the horizontal beam was DY = -0.2455 mm. The variant subjected to analysis was less favourable than the skew one, yet assumedly, the horizontal position of the arms of the H-type positioner (see Fig. 10) should only be momentary.

Similar results were obtained in relation to the H-type positioner having a load capacity of 1000 kg. In the primary position of the arms with the skew position of the discs, values of the vertical deflection in the centre of the discs were restricted within the relatively narrow range of -0.0685 mm to -0.0732 mm, where the maximum value of deflection at the half of the length of the horizontal beam was DY = 0.1645 mm.

Analysis of the FEM-based modelling of the module system of tracks

The tracks subjected to analysis contained three design-related solutions applicable in industrial conditions, i.e. (moving) floor tracks, gantry tracks with the moving platform fixed on
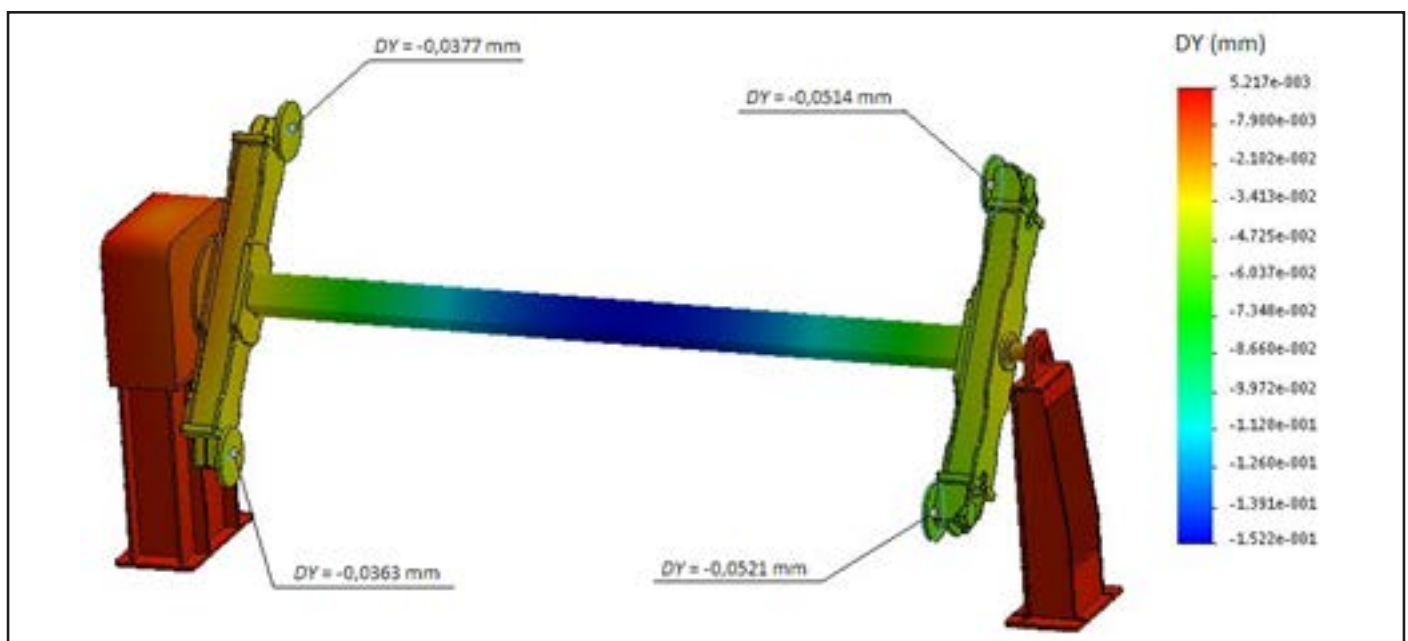

Fig. 9. Distribution of the vertical deflection of the H-type positioner (300 kg) in the skew position of the arms with the marked values of deflection in the middle of the work tables
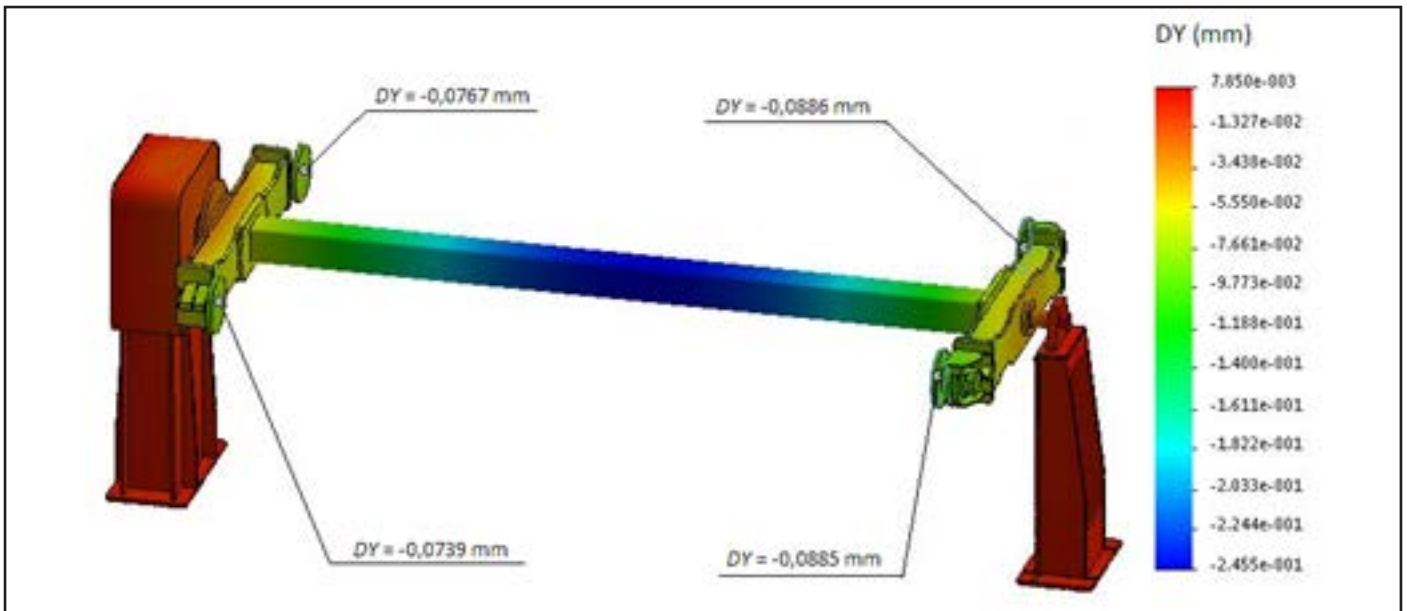
Fig. 10. Distribution of the vertical deflection of the H-type positioner (300 kg) with the arms positioned horizontally and with the identified values of deflection in the centre of the work tables

the wall and gantry tracks where the moving platform was fixed in the reversed (suspended) manner. The computational variants concerning the tracks included a load of 250 kg and that of 500 kg as well a track length of 2.5 m and that of 5 m. In addition, the tests also involved three designs variants related to 5 m long tracks subjected to a load of 500 kg, provided with two moving platforms on a common track.

The design of the floor tracks seemed the simplest among all of the variants subjected to analysis. Both 2.5 m and 5.0 m long models were well supported by a significant number of elements of arms and beams positioned transversely in relation to the base. Both in relation to the 2.5 m long and 5.0 m long structure, the maximum stresses did not exceed 11 MPa under a load of 250 kg and 59 MPa under a load of 500 kg. Maximum deflections present in the central part of the moving platform did not exceed 0.01 mm and 0.03 mm in relation to a load of 250 kg and that of 500 kg respectively and satisfied the previously assumed deflection-related parameters (Fig. 11).

In cases of the gantry tracks and on-the-wall position, the moving platform was set in the most unfavourable position, i.e. at the half of the length of the horizontal beam supported
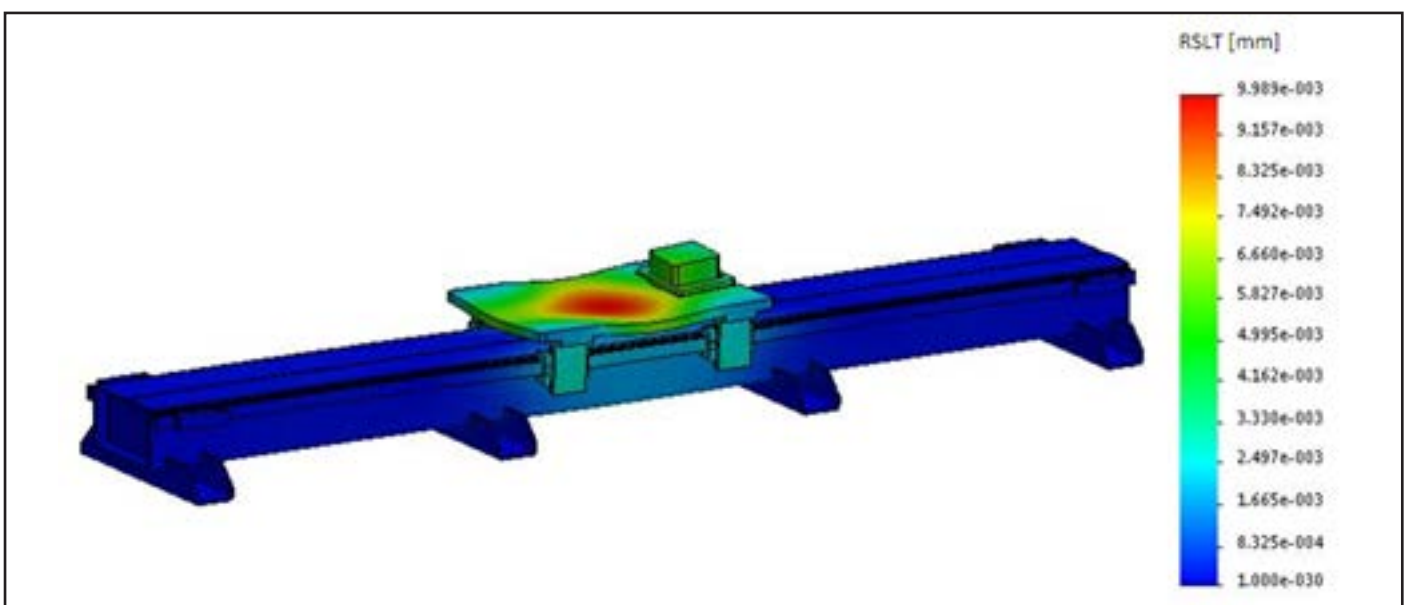

Fig. 11. Distribution of resultant displacement in relation to the 2.5 m long track model (250 kg)

by two vertical poles (Fig. 12a). The 2.5 m long variant revealed slight values of stresses present in the structure (approximately 10 MPa). The fact that the moving platform was fixed on one side of the horizontal beam resulted in the side deflections of the beam triggered by the bending moment affecting both vertical poles. In relation to the 2.5 m long track, the vertical deflection of the horizontal beam amounted to maximum DY = -0.094 mm under a load of 250 kg and DY = -0.163 mm under a load of 500 kg (maximum stress below 40 MPa). In cases of the 5 m long gantry tracks, the behaviour of the structure was similar under a load of 250 and 500 kg. In relation to the above-presented loads, the maximum stress amounted to 48 MPa and 110 MPa respectively. Similar to the aforesaid loads, the vertical deflection at the half of the horizontal beam amounted to DY =-0.4 mm (side deflection DZ = 0.26 mm) in relation to a load of 250 kg and DY = -0.61 mm, (side deflection DZ = 0.238 mm) in relation to a load of 500 kg.

The second design variant of the gantry track was that being 2.5 metres in length and the one having a length of 5 metres, subjected to a load of 250 kg and 500 kg and having the form of a moving platform (Fig. 12b). As regards the 2.5 m long gantry track subjected to a load of 250 kg, the maximum vertical deflection on the horizontal beam was DY = -0.369 mm. When the track was subjected to a load of 500 kg, the deflection was DY =-0.60 mm. The side deflections of the horizontal beam amounted to 0.295 mm and 0.53 mm respectively. The use of the upended platform resulted in the further shift of the centre of gravity (fixed to the robot platform) away from the horizontal beam and, consequently, led to an increase in the bending moment. The maximum stresses in the structure of the 2.5 long track subjected to analysis did not exceed 76 MPa.

Summary and conclusions

The FEM-based calculations concerning the behaviour of test devices tested under preset loads indicated a number of conditions accompanying the designs of the above-named devices. The calculations led to the identification of the specific distribution of stresses and strains in the structure and/or the deflection of individual units with respect to operation on a robotic station [2, 5].

The design of positioners and tracks intended for the integrated collaboration with an industrial robot is difficult in view of the fact that the aforesaid positioners should be characterised by the wide range of movements, significant
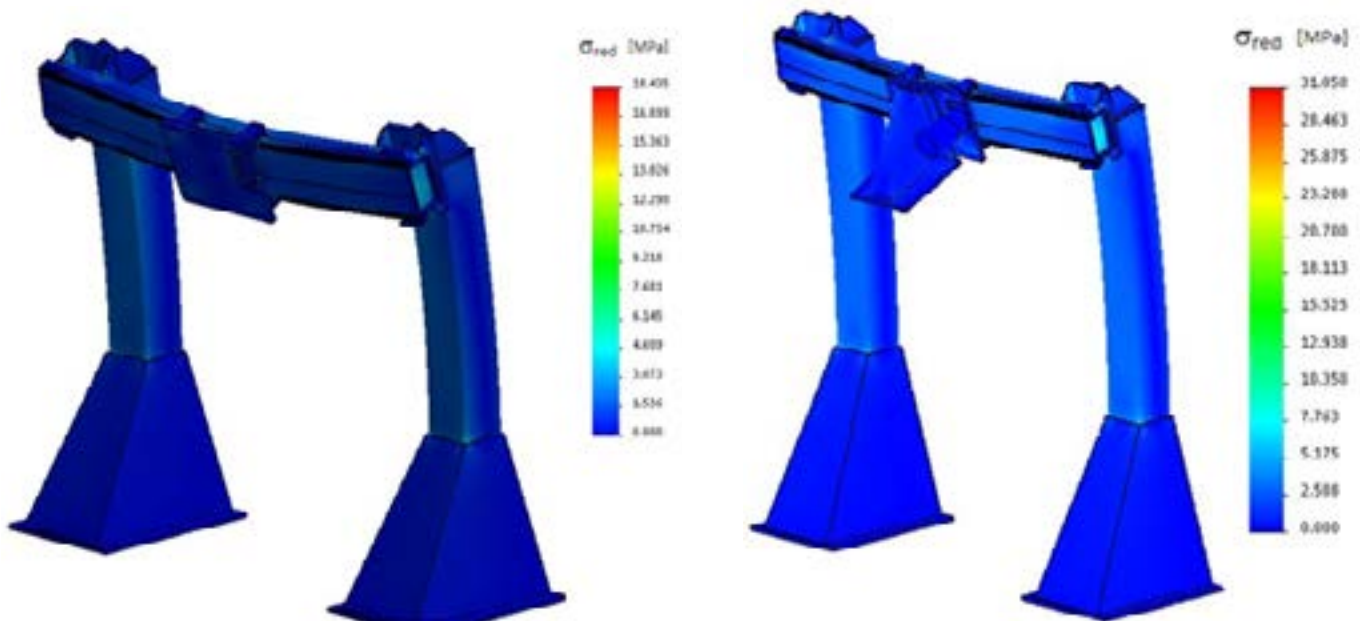

Fig. 12. Deformation of the 2.5 m long gantry track (250 kg) in: a) on-the-wall system, b) upended system

load capacity and operating space. The above-named difficulty resulted primarily from the assumptions related to the repeatability of the robot similar to that of the designed devices and combining the foregoing with the acceptable elastic strain not exceeding 0.05 mm.

In most cases, the highest reduced loads demonstrated during calculations did not reach the half of the yield point of the material. In turn, small clusters of very high stresses, possibly resulting from the peculiarity of FEM numerical calculations, were reduced through the implemented and/or recommended design-related modifications.

In practice, confirmed by designers of equipment provided with extension arms and gantry machinery gantry, an FEM-modelled elastic deflection of as many as several millimetres is regarded as appropriate. The research also included the performance of simple experiments involving the deflection of the arm of an industrial robot arm under the half of the nominal load. In the tests, a Fanuc ARC Mate 0iB robot underwent an elastic deflection of 0.7 mm under a load of 1.5 kg, where the declared positioning repeatability amounted to ± 0.08. However, the foregoing did not preclude the obtainment of high positing accuracy as elastic deflections under a constant load could be allowed for in a machine operation software programme as the normal form of the machine.

In spite of this, as a result of the performed design works, FEM calculations and implemented and/or recommended modifications of the criterion of the allowed elastic strain can also be regarded as satisfied in relation to all of the models subjected to the test, yet after allowing for certain conditions:

1. In case of the L-type positioners, the critical element was the moving joint of the L-arm with the housing. The detailed analyses revealed that the housing itself and the L-arm treated separately satisfied the condition of the allowed deflection amounting to less

than 0.05 mm. However, the deformation of the axis of rotation could not be verified computationally (FEM) because of the commercial nature of the element (unknown in terms of the design and material). The ultimate verification (and modification, if necessary will take place after the kinetic tests of the machines (once built).

2. In relation to the H-type positioners it was important that the working load located between the tables be characterised by high rigidity. Practical applications are based on the use of rigid intermediate frames, to which objects (to be manipulated) are fixed. The impossibility of simulating such an object which, in practice, could take any shape, preclude the performance of calculations fully representing the actual conditions of operation. It is recommended to locate the same housing on the passive (not driven) side as the one located on the side provided with the drive.

3. In cases of the gantry tracks it was possible to obtain the previously assumed vertical deflection of less than 0.05 mm. However, to accomplish this objective, the design of 5 m long and 2.5 m long tracks subjected to a load of 500 kg should be provided with an additional support of the horizontal beam at the half of the length between the extreme vertical poles. In addition, the structure of the vertical poles (thicker cross-sections) should be reinforced. Also, reinforcement should be provided to the area where the vertical pole is connected with the horizontal beam and to the elements of the fixing of the track with the horizontal beam (greater cross-sections and different location of reinforcements and ribs in the elements of the structure).

References

[1] Cegielski P., Golański D., Kolasa A., Sarnowski T.: Modelowanie i wdrożenie wysięgników do lokomocji robotów przemysłowych. Przegląd Spawalnictwa, 2015, no. 1, pp. 6-13.

[2] Cegielski P., Golański D., Kołodziejczak P., Kolasa A., Rochalski D.: Weryfikacja modeli konstrukcyjnych pozycjonerów spawalniczych w oparciu o modelowanie matematyczne MES. Przegląd Spawalnictwa, 2018, no. 1, pp. 36-42.

[3] Cegielski P., Golański D., Kolasa A., Sarnowski T.: Nowe konstrukcje i metody projektowania zewnętrznych osi do lokomocji robotów przemysłowych. Pomiary Automatyka Robotyka, 2017, no. 7-8, pp. 90-95.

[4] Cegielski P., Golański D., Kołodziejczak P., Kolasa A., Sarnowski T. Studium rozwiązań konstrukcyjnych nowej generacji zewnętrznych osi robotów przemysłowych. Przegląd Spawalnictwa, 2017, no. 11, pp. 84-92.

[5] Cegielski P., Golański D., Kołodziejczak P., Kolasa A., Rochalski D.: Analiza uwarunkowań zapewnienia wybranych właściwości użytkowych wieloosiowych manipulatorów – zewnętrznych osi robotów. Paper presented at 15-th Krajowa Konferencja Robotyki, 5-9 September 2018, Polanica-Zdrój.

[6] Cegielski P., Kolasa A., Sarnowski T.: Nowe konstrukcje pozycjonerów jako zewnętrznych osi robotów przemysłowych. Przegląd Spawalnictwa, 2016, no. 1, pp. 27-32.

[7] LUSAS Modeller User Manual v. 14.0. FEA Ltd. UK.

[8] Cook R.D.: Finite element modelling for stress analysis. John Wiley, 1995.