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The FEM-based Numerical Analysis of Welding Distortions in Spatial-Flat Elements of Large-Sized Welded Structures

Abstract: The issue of welding distortions concerns both large welded structures such as bridges, storage tanks and elements of welded building structures as well as small and precise elements. Particularly susceptible to welding distortions are thin-walled structures, in which hard-to-predict welding distortions are responsible for serious technical problems. This paper presents the results concerning the welding of spatial and flat elements used in large-sized welded structures in terms of welding distortions. Due to their geometry, large welded structures may be the source of complex welding distortions, e.g. corrugations. The research-related works discussed in the article were carried out using the finite element method (FEM). The validation of FEM model of the welding process was performed using an optical system measuring welding distortions of an actual structure.

Keywords: welding strains, numerical modelling, FEM, Finite Element Method, reduction of welding strains, welded structures

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Introduction

In spite of multiannual experiments, practice and discussions, welding processes used all over the world are the reason for the formation of hard-to-predict welding strains (distortions). A significant heat input during the process of welding and a related thermal cycle are responsible for the non-uniform distribution of temperature in the weld and elements being joined [1]. Changes in volume presented in Figure 1 proceed in all directions, leading to the formation of various welding distortions of the structure. The problem applies to large-sized welded structures such as bridges, storage tanks and welded structures of buildings as well as small precise elements. Particularly susceptible to welding strains are thin-walled structures, where hard-to-predict welding strains create significant technical problems. Requirements concerning, among other things, welding strains in steel structures, are specified in the PN-EN 1090-2 standard [2]. Many specialist sectors of industry (e.g. automotive industry) often apply industry standards, developed by individual concerns.

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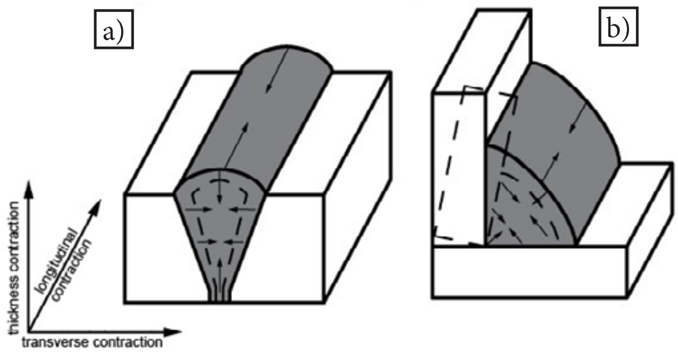

Fig. 1. Directions of volume changes in a) butt welds and b) fillet welds during post-weld cooling

Welding stresses are formed as a result of changes in volume during contraction occurring in the welded join area. Stresses are responsible for the formation of strains (distortions) in the weld and joined elements. Transverse contraction, present, among other things in T-joints and butt-welded joints, is responsible for the formation of angular strains, where the resultant bend depends on the shape of the weld groove, the thickness of the welded material and the number of weld layers. In cases of long welds, longitudinal contraction in joints may trigger the formation of corrugation, bulges and bends.

Distortions of welded joints depend primarily on the cross-section of the weld, rigidity, the size of a structure size as well as a heat input, directly resulting from the use of a welding method applied in the joining process. An appropriate welding technology may reduce internal stresses in elements being welded [3]. The reduction of a heat input is increasingly frequently obtained by applying low-energy MAG welding methods such as CMT, ColdArc, STT and CBT or hybrid welding methods (HLAW = laser+MAG). When joining sheets thinner than 4 mm, welding is preplaced with braze welding. A significantly lower heat input and high process stability may lead to the significant reduction of deformations and, in cases of galvanised sheets, to the minimisation of damage to the protective (zinc) coating as well as improve the joint aesthetics by limiting spatter. The most recent and innovative solution involves the application of variable polarity pulsed current in low-energy gas-shielded metal arc welding methods such as AC Pulse, Cold Process and CMT Advanced [4–7]. One of the ways enabling the limitation of deformations includes the use of appropriate welding sequence and the application of a proper structural solution as well as (in particular) the prevention of such mistakes as the excessive thickness of welds or the making of continuous welds instead of intermittent ones. Stresses leading to deformations can also be reduced using the following methods:

- stress relief annealing (heating a structure to a temperature of 650 °C), holding (an element at the temperature) for a time related to the thickness of the element followed by slow cooling),
- verstraining of a structure (local exceeding of the yield point and the reduction of stresses after unloading).

This article presents issues concerned with welding stresses and strains/distortions as well as discusses methods enabling the limitation of such phenomena and their consequences. In addition, the article discusses the application of numerical methods when forecasting post-weld structural deformations and simulating solutions limiting the formation of welding distortions through the application of bracings during welding.

Welding stresses and strains – state of the art

The prevention of welding stresses is one of the most important and most difficult issues encountered in welding engineering. Strains, resulting from the combined effect of the solidification contraction of the weld metal and contraction in the near-weld area (particularly HAZ), being the consequence of plastic strains and phase transformations, may prevent the proper joining of large-sized structure elements or lead to the disqualification of a final product because of a failure to satisfy related standards specifying guidelines concerning the maximum values of deformations. Welding distortions and residual stresses present in the area of the welded joint as well as in areas of the structure distant from the joint unfavourably affect the welded structure also in terms of its load-carrying capacity (as they can add to stresses resulting from internal factors). The above-named stresses may reduce the safe service life of a structure exposed to fatigue or trigger the formation of brittle cracks at the initial stage of operation.

Primary issues related to butt-welded joints include angular deformations triggered by transverse contraction and manifested by the bending of elements. In turn, thin sheets are troubled by corrugation induced by longitudinal contraction. During welding works it is impossible to eliminate contraction and residual stresses, yet it is possible to limit the presence of such factors by applying appropriate technical solutions. Among many solutions including the appropriate design of a structure and the proper selection of materials it is also possible to divide a given structure into groups. By providing joints with the possibility of freely deforming the structure, it is possible to "release" internal stresses. In some cases it may be necessary to apply the process of straightening and, only after that, to join previously made modules into a larger structural element.

Fig. 2. Prevention of deformations: deformation is presented on the left, whereas the pre-weld deformation preventing the post-weld deformation is presented on the right [8]

Welding practice requires the appropriate pre-weld positioning of elements to be welded or the preliminary deformation of such elements (counter-bend). Elements should be bent in the opposite direction in relation to expected deformations (Fig. 2). The effect of the longitudinal contraction of thin sheets can be reduced by the application of longitudinal stiffening in the form of shapes (Fig. 3).

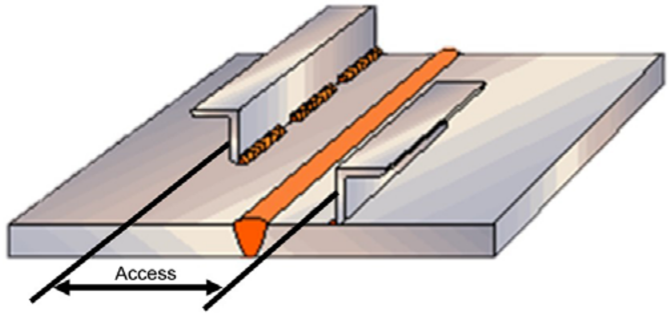

Fig. 3. Longitudinal stiffening preventing the deformation of thin butt-welded joints [9]

The forecasting of possible structural imperfections during assembly and preventing the formation of such imperfections at the stage of designing and planning makes it possible to reduce costs and delays resulting from the removal of deformations. Welding distortions can be limited by appropriate methods (e.g. fixing clamps), yet they cannot be limited. For this reason, it is very important to predict the possible consequences of such deformations. Possessing knowledge concerning structural deformations at the stage of assembly planning and during the designing of the welding process enables the prevention of deformation-triggered consequences, e.g. by making allowances in elements to be welded.

Engineering practice uses analytical methods of calculating the deformations of entire elements of welded structures having one and two-sided longitudinal welds, transverse deformations during surfacing and the butt welding of sheets as well as local deformations resulting from the loss of stability by thin-walled welded structures.

Welding deformations/distortions can be tested by performing the actual welding process or using FEM-based numerical simulations (FEM – Finite Element Method). In many sectors of industry, the design process is increasingly often supported by FEM-based solutions [10–12] [13–24]. The above-named approach makes it possible to verify the correctness of a design before its implementation. The FEM-based simulation of welding processes is primarily used for the determination of temperature fields as well as stresses and strains of welded element formed during the welding process. On the basis of calculated temperature accompanying the welding process, phase transformation diagrams and material hardness-related data, it is possible to identify the structural components and hardness of a materials subjected to welding thermal cycles. The application of numerical methods, particularly at the first stage of the development of a welding technology and schedule, enables the reduction of tests aimed to determine the most favourable welding process parameters and the elimination of errors (at the design stage), which are very difficult or impossible to remove at the subsequent stages of production. An additional advantage resulting from the use of numerical methods is the possibility of simulating the welding of larger fragments or even entire structures to be welded. The relative analyses and the optimisation of the welding process make it possible to consider many variants when making welded structures without the necessity of performing actual tests. Particularly in terms of large-sized structures, the possibility of performing actual tests before the implementation of a given production technology is limited, primarily by costs and laboriousness. The welding of large-sized elements such as storage tanks and ship hulls may trigger the formation of corrugations, bulges and bends. Procedures aimed to prevent the above-named phenomena include, among other things, the appropriate stiffening/bracing of a welded structure, the development of which can be supported by numerical methods. In addition to forecasting the deformations of welded elements, numerical analyses enable the determination of the counter-bend of a given element preventing its deformation. In terms of large-sized structures, numerical analyses are primarily used for determining the counter-bend and the fastening of an element using appropriate clamps. The FEM-based software is used in analyses aimed to identify distortions, internal and support forces as well as stresses of structural, spatial and flat systems composed of plates/sheets, walls, shells and bars [25].

Storage tanks are used for the storage of, among other things, chemicals, oils, fuels and water in the papermaking, food, pharmaceutical and plastics industry. Usually, tanks constitute grouped elements of storage terminals, i.e. the so-called tank farms. Because of their size (typical liquid fuel storage tanks have volume $V = 10000 \div 30000\ m^3$) and limited transportability, large-sized storage tanks are made exclusively at the site of their operation, usually using the superstructure method (referred to as the sheet method) consisting in the joining of single sheets making up the tank shell. Assembly at the construction site imposes restrictions as regards the use of welding methods and the necessity of welding under unfavourable conditions [26,27]. The selection of welding methods has a decisive influence on the rate and quality of the process used to make a welded structure. Storage tanks usually contain butt, T-shaped and corner joints. As regards the total number of welded joints, they are present in the largest quantity on the tank shell. The aforementioned joints are usually (mostly) butt joints made in the horizontal position (PC) and in the vertical up position (PF) as well as T-joints with the fillet weld made in the horizontal position (PB) (between the base-flange ring and the shell) [26]. The welding of steel structures, particularly those made of spatial-flat elements is the primary reason for the formation of shape-related imperfections. Designers and contractors should comply with principles contained in related standards and guidelines (e.g. PN-EN 1993 [28]), specifying, among other things, allowed dimensional deviations, lacking flatness and straightness of steel structures. When assembling a storage tank, shell shape-related imperfections (in particular) may preclude the proper fixing of individual elements, resulting in the costly removal of the above-named deformations [29]. The making of butt welds triggers angular distortions as well as transverse and longitudinal contractions. Usually, when making tank shells, edges of plates are subjected to X-groove joint preparation where subsequent beads are made interchangeably on the external and internal side of the shell. Angle strains (distortions) formed as a result on the outside are compensated by strains (distortions) formed as a result of welding performed inside the shell. However, the above-presented principle does not always work and sometimes angular bends may be formed. In turn, the phenomenon of transverse contraction requires taking into consideration the allowance of the length of a closing plate as its lack will result in the local bend of the cylindrical shape of the shell. Article [29] presents the scale of a problem related to contractions, illustrated with an example of a ring structure composed of 26 plates (each having a length of 6 m), where the entire circumferential contraction amounted to 41.6 mm. As can be seen, in order to obtain a product meeting related requirements it is necessary to possess detailed knowledge concerning the behaviour of materials subjected to welding thermal cycles.

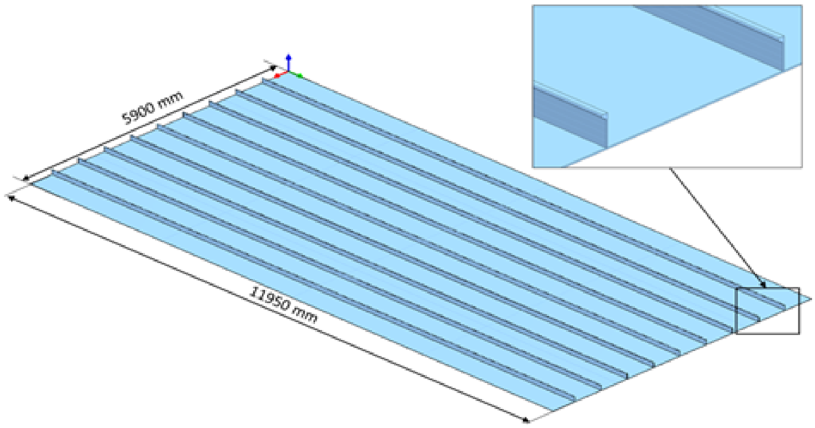

Fig. 4. Geometry of the flat sections and the bracing of group I

The problems of welding distortions also accompany the prefabrication of ship hull structures, during which distortions are additionally triggered by, among other things, the welding of bracings of group I and II to flat sections (Fig. 4). Welding distortions can also be formed as a result of the welding of assembly sections including flat and/or basin-shaped sections such as deep tanks in the midship, superstructure sections, backing elements and the double bottom of the forepeak and afterpeak [19, 20].

The FEM is also used to simulate welding processes in the making of steel structures and, as a result, can be applied when planning the process of assembling spatial-flat structures such as storage tanks or ship hulls.

The authors of article [16] presented the results of numerical analyses concerning the welding of storage tanks. The authors paid attention to the issue of applying FEM when determining welding distortions in large-sized structures. Despite the complexity of the welding process, it is possible to perform the thorough thermomechanical FEM-based analysis, yet, because of the significant demand for computing power in such analyses, they are usually limited to small elements [17,18,21,22]. Similarly, the modelling and calculations concerned with large structures are time-consuming. However, there are solutions enabling the obtainment of sufficiently good results at a significantly shorter time. Usually, the aforementioned solutions involve methods consisting in the setting of a specific welding thermal cycle along the entire length of a joint or, in cases of long beads, in the setting of thermal cycles in subsequently designated sections of the joint (Fig. 5). Another solution involves the application of the contraction method, consisting in the setting of welding distortions (resulting from post-weld cooling) in the welded joint area [16,16,19,20,23,32].

Presented below are test results concerning the welding of spatial-flat elements used in large-sized welded structures, in which, because of their geometry, complex welding distortions (e.g. corrugations) may be formed.

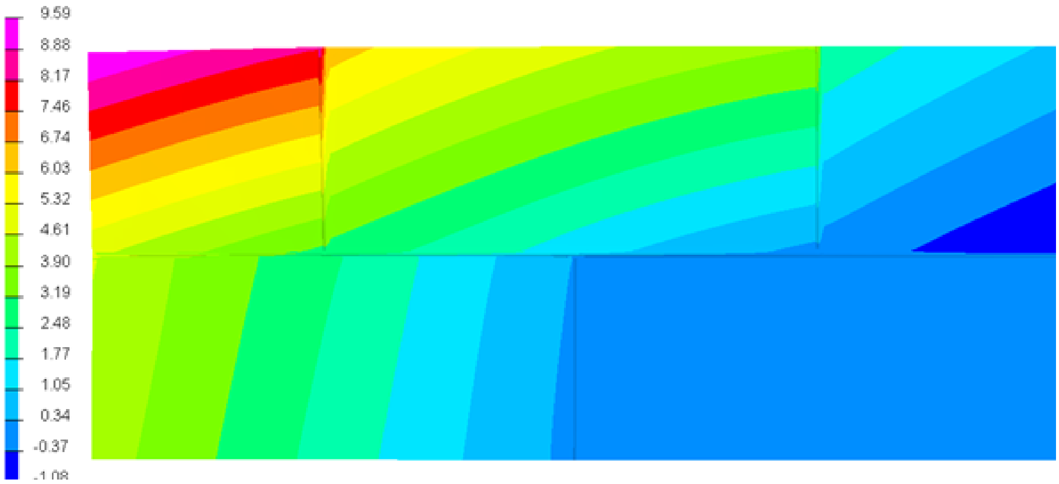

Fig. 5. Calculated field of displacement in the direction perpendicular to the surface of the element subjected to welding with the fastening of one sheet, mm [32]

Test object

The tests were focused on the welding of the flat section sheet along with bracings made of ship plate grade A according to ASTM A131 [33]. The dimensions of the elements and the locations of bracings are presented in Figures 6 and 7. The section was placed on a steel plate (table) having a thickness of 15 mm. A welding torch was fixed to a welding tractor and the process of welding was in each case started on the same side of the plate.

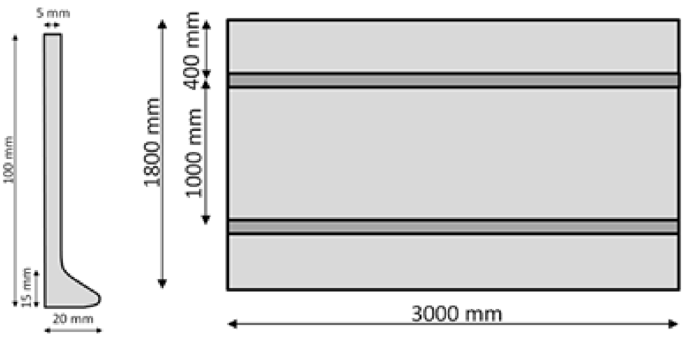

Fig. 6. Dimensions of the flat section and the arrangement of the first-order bracings

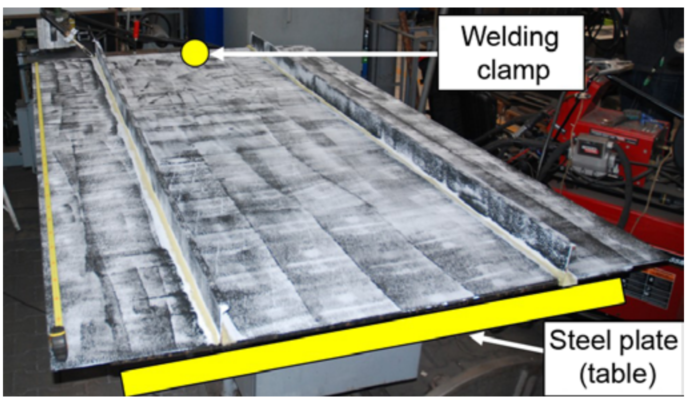

Fig. 7. Fastening flat section and first-order bracings during welding

Tests and results

The first stage of the tests concerning the effect of the welding process on welding distortions involved the performance of measurements of welding distortions. The measurements were performed using a Dantec Dynamics Q-400 Multicamera Digital Image Correlation system and 3 5MPx cameras. To this end, the surface of the elements subjected to welding was painted so that to obtain randomised black and white pattern (Fig. 8). The first stage included the performance of two measurements of the sheet, i.e. one before the commencement of the welding process and, the second, following the completion of the welding process and the cooling of the element.

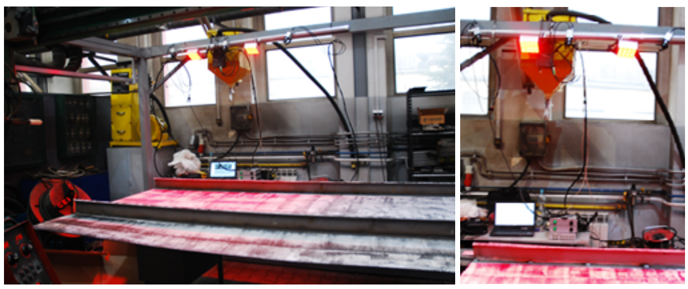

Fig. 8. Fragment of the flat section and bracings prepared for the measurements of welding distortions and the Dantec Dynamics Q-400 Multicamera Digital Image Correlation system

The visual assessment and the measurements involving the use of the optical system revealed the corrugation of the flat section surface (Fig. 9 and 10). The measured field of displacements revealed the maximum value in the sheet corner (point 1 in Figure 10); its value being 14.1 mm. At point 2 (Fig. 10), i.e. where the edge of the table was located, it was possible to notice displacements amounting to 9.1 mm (also measured using the gap gauge). The remaining tests focused on the analysis of the displacements in the direction perpendicular to the surface of the flat section; the reason being the significant value of the displacements in relation to the remaining directions of the displacements.

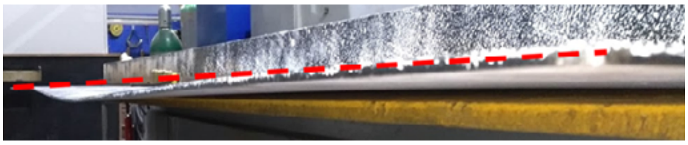

Fig. 9. Corrugated edge of the flat section after the completion of the welding process

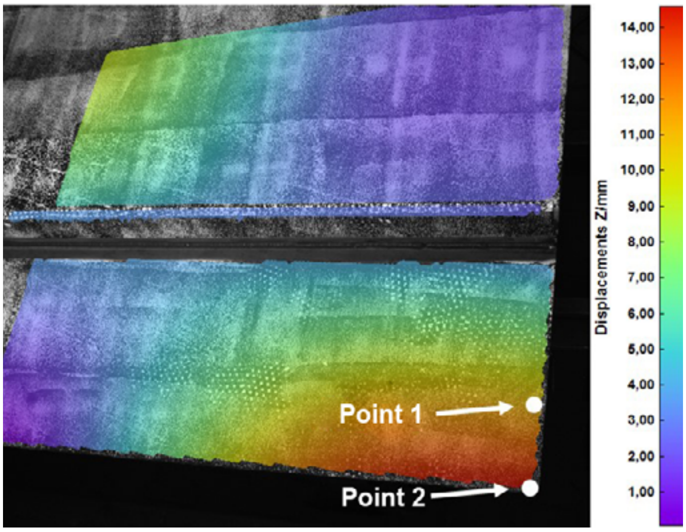

Fig. 10. Fragment the element subjected to welding with the superimposed field of displacement in the direction perpendicular to the surface of the flat section after the completion of the welding process, point 1 – maximum displacement (14.1 mm)

The second stage involved the numerical analysis (FEM-based) concerned with the welding of the element subjected to the tests. The flat section and the first-order bracings (I) were modelled using shell elements based on midsurfaces. In turn, the process of welding was modelled using the "Imposed Thermal Cycle" method, dividing the weld into sections successively subjected to welding thermal cycles. The weld was also modelled using surface elements. During the process of modelling, the element subjected to welding was treated as symmetric (in accordance with Figure 11). As a result, the size of the model was reduced by twice, whereas the time of calculations was reduced many times. The boundary condition of symmetry set in the nodes contained in the symmetry plane precluded the displacement of the nodes in the normal direction in relation to the surface as well as precluded the rotation of the nodes.

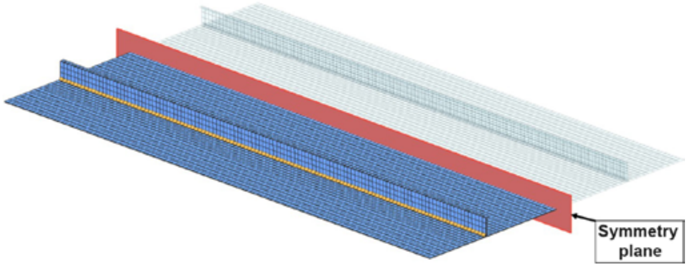

Fig. 11. Discrete model of the flat section and first-order bracings used in calculations and the plane according to which the boundary symmetry condition was preset

The subsequent stage involved the setting of boundary conditions (Fig. 12) aimed to model the section fastening conditions during the actual process of welding (Fig. 7), designated as variant "0". The flat section was fastened using one welding clamp and placed on a steel sheet. As a result, in addition to the boundary condition of symmetry, the model included the condition of all-directional fastening, modelling the effect of the welding clamp on the system. The effect of the table on the element during welding was modelled using the "stop" boundary condition, precluding the displacement of nodes in the y-direction (normal in relation to the section). The model took into consideration the effect of force resulting from gravity.

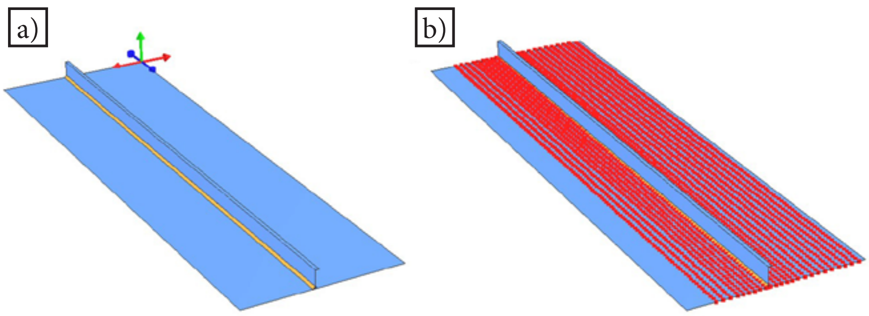

Fig. 12. Preset boundary conditions a) all-directional fastening and b) "stop" boundary condition

Figure 13 presents the field of displacements in the normal direction in relation to the section subjected to welding. The maximum value of displacement amounted to 12.7 mm. It was possible to observe the characteristic corrugation of the sheet, analogous to that presented in Figure 9.

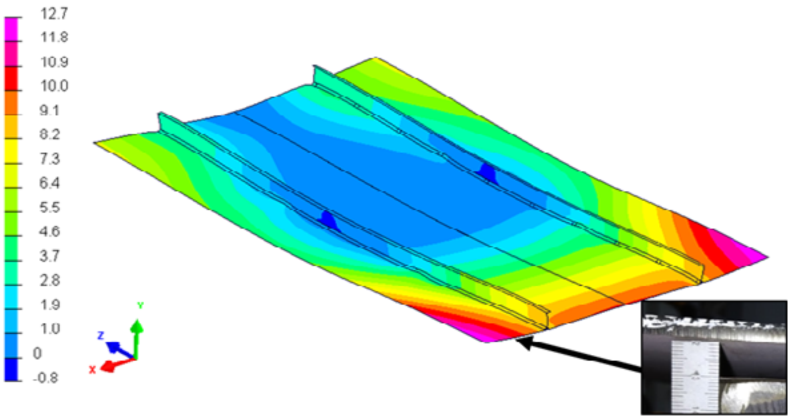

Fig. 13. Field of displacements in the normal direction in relation to the section subjected to welding in variant "0", mm

The FEM calculation results were compared (Table 1) with the values measured using the optical system (Fig. 14) and a gap gauge. The difference between the calculated displacement and the displacement measured using the optical system at points 1 and 2 amounted to approximately 11%.

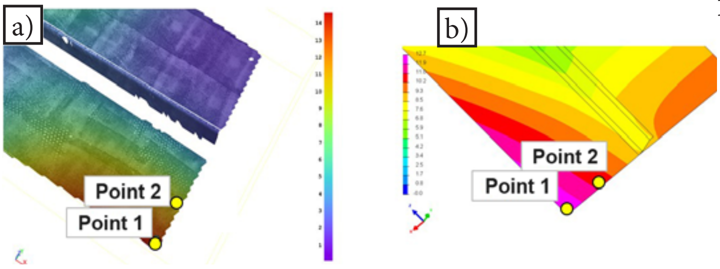

Fig. 14. Displacement in the normal direction in relation to the surface of the section welded in variant "0" a) measurements of the actual element performed using the optical system and b) FEM calculation results

Table 1. Results of displacements in the normal direction in relation to the surface of the section at points 1 and 2 as presented in Figure 14

Point	Measurement with the optical system, mm	FEM calculation results, mm	Measurement with the gap gauge, mm
1	14.1	12.7	not applicable
2	9.1	10.1	9.8

The validation of the FEM model of welding revealed that the applied procedure could be used for qualitative analyses. The analyses included the determination of welding distortions of the flat section with first-order bracings, welded using various fastening configurations. To this end, two variants containing technical solutions of element fastening during welding were selected. The first method assumed the pressing of the element in the area along the weld axis as presented in Figure 15. Such fastening can be obtained by applying pressure involving the use of the section. The second method involved the fastening of the section in selected areas as presented in Figure 16. Such fastening can be obtained by using locally arranged electromagnets under an element to be welded. After the completion of the welding process and the cooling of the element, the structure (in both cases) was released from the fastening, where the section was fastened using boundary conditions as in the analysis of the actual welding process in variant "0" (Fig. 12). The above-presented approach enabled the performance of qualitative comparative analysis.

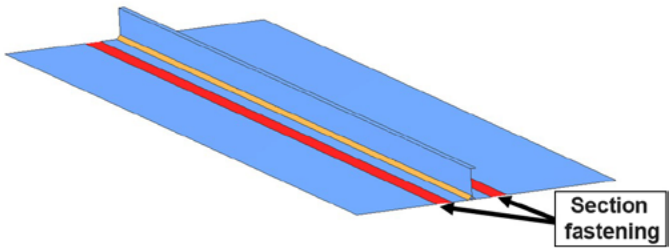

Fig. 15. Variant "1" of the fastening – section pressed against the welding table along the weld (areas marked red)

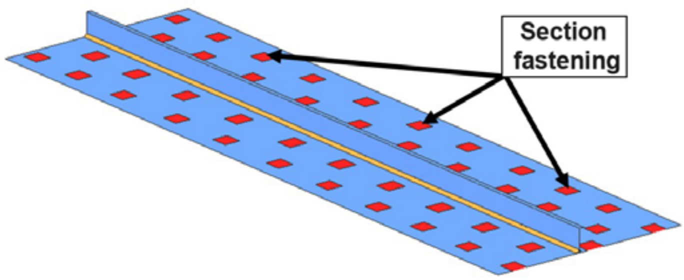

Fig. 16. Variant "2" of the fastening – section "fastened" to the welding table in selected areas (areas marked red)

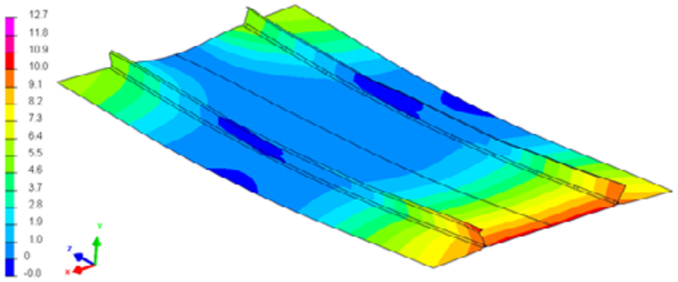

Fig. 17. Field of displacements in the normal direction in relation to the surface of the section welded in variant “1”, mm

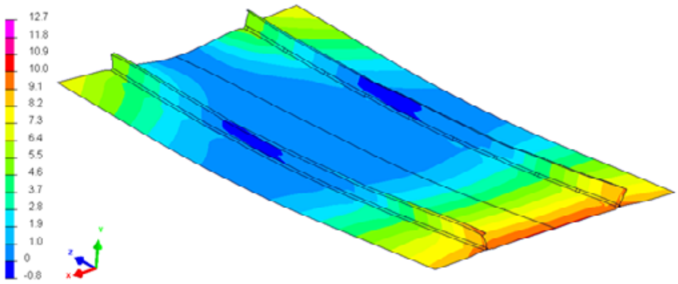

Fig. 18. Field of displacements in the normal direction in relation to the surface of the section welded in variant “2, mm

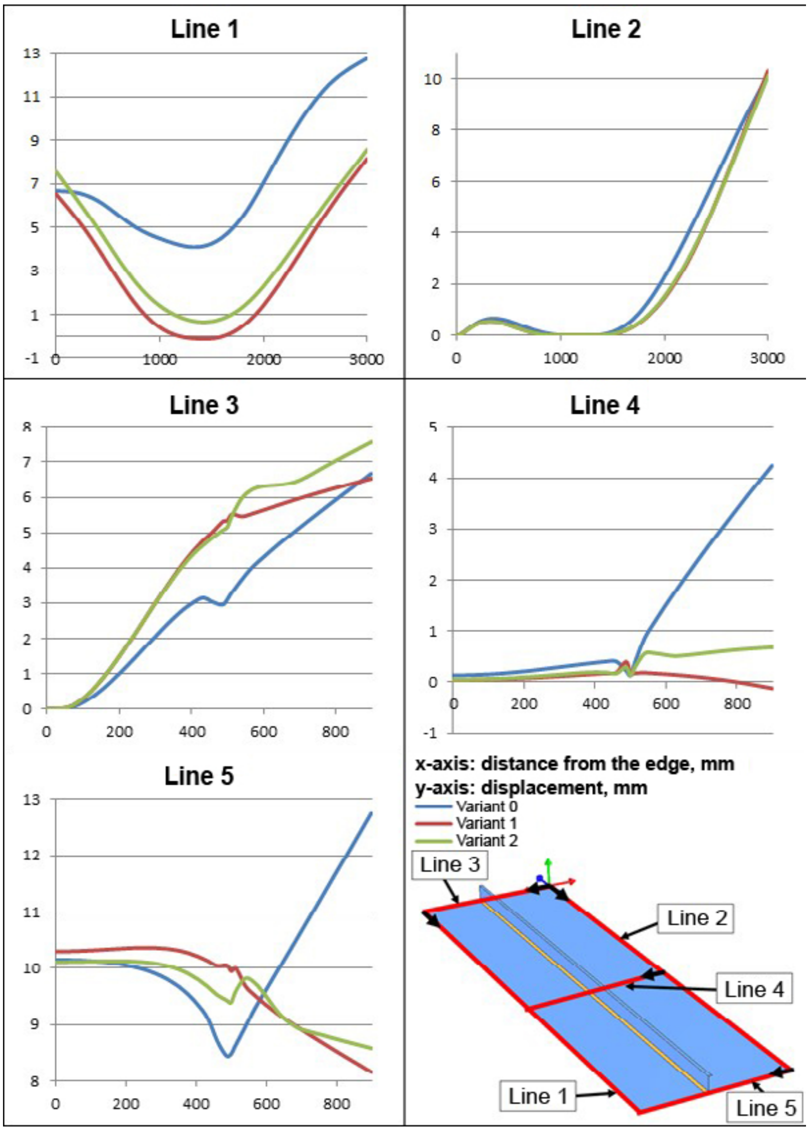

Fig. 19. Displacement of the nodes along selected lines in 3 analysed variants of element fastening during welding

Concluding remarks

The analysis of the test results led to the formulation of the following conclusions:

1. Because of their low rigidity, flat and spatial elements are particularly susceptible to develop welding distortions. In terms of large thin sheets welded with fastenings, it is often necessary to make long welds. However, the making of long welds may entail contraction which, in turn could lead to the corrugation of an element subjected to welding.
2. The qualitative analysis of various fastenings of elements during welding revealed that the stiffening of a structure during welding provides the possibility of reducing welding distortions and, primarily, changing their nature. As a result, the straightening of the structure can be less complex and, consequently, less laborious and time-consuming.
3. The scale of welding strain-related issues increases along with the dimensions of a structure and the number of welded joints to be made. Larger structures should be fixed appropriately before welding.

References

[1] Mizerski J.: Spawanie. Wiadomości podstawowe. Wyd. REA, Warszawa, 2005.

[2] PN-EN 1090-2:2018-09 Wykonanie konstrukcji stalowych i aluminiowych - Część 2: Wymagania techniczne dotyczące konstrukcji stalowych. http://pspaw.pl/index.php/pspaw/article/view/228

[3] Pilarczyk J., Pilarczyk J.: Spawanie i napawanie elektryczne metali. Wyd. Śląsk Sp. z o.o., Katowice, 1996.

[4] Badanie wpływu warunków spawania wysokowytrzymałych stopów aluminium i lutospawania

stali metodą MIG na własności połączeń i ich jakość. Praca badawcza Instytutu Spawalnictwa, Gliwice, 2004.

[5] Kiszka A., Pfeifer T.: Spawanie cienkich blach stalowych z powłokami ochronnymi metodą MAG prądem o zmiennej biegunowości. Biuletyn Instytutu Spawalnictwa, 2012, no. 2. *http://bulletin.is.gliwice.pl/article/braze-welding-zinc-coated-steel-sheets*

[6] Gawrysiuk W., Pfeifer T., Winiowski A.: Charakterystyka technologii lutospawania łukowego MIG/MAG. Przegląd Spawalnictwa, 2005, no. 2-3.

[7] Bruckner J.: Metoda CMT - rewolucja w technologii spawania. Przegląd Spawalnictwa, 2009, no. 7-8.

[8] Projektowanie i Konstrukcje Inżynierskie - Skurcze i inne odkształcenia spawalnicze. www.konstrukcjeinzynierskie.pl/internauci/123-na-zyczenie-internautow-2014/1172-skurcze-i-inne-odksztalcenia-spawalnicze (accessed on 25.01.2018).

[9] Distortion Control - Prevention by fabrication techniques - Job Knowledge 36. www.twi-global.com/technical-knowledge/job-knowledge/distortion-control-prevention-by-fabrication-techniques-036.aspx (accessed on 21.01.2019).

[10] Kelly S.M., Martukanitz R.P., Reutzel E.W.: Minimizing buckling distortion in welding by hybrid laser-arc welding. Minimization of Welding Distortion and Buckling - 9. Modelling and Implementation, Woodhead Publishing Series in Welding and Other Joining Technologies, 2011. *https://www.sciencedirect.com/science/article/pii/B9781845696627500096?via%3Dihub*

[11] Mazar Atabaki M., Nikodinovski M., Chenier P., Ma J., Liu W., Kovacevic R.: Experimental and numerical investigations of hybrid laser arc welding of aluminum alloys in the thick T-joint configuration. Optics & Laser Technology, 2014, vol. 59. *https://www.sciencedirect.com/science/article/pii/S0030399213004581?via%3Dihub*

[12] Kokot G., John A., Górka J.: Wspomaganie procesu spawania z wykorzystaniem MES. Przegląd Mechaniczny, 2008, no. 5.

[13] Kelly S.M., Martukanitz R.P.: Minimizing buckling distortion in welding by hybrid laser-arc welding. Minimization of Welding Distortion and Buckling. Modelling and Implementation, Woodhead Publishing, 2011. *https://www.sciencedirect.com/science/article/pii/B9781845696627500096?via%3Dihub*

[14] Jiang W., Yahiaoui K.: Effect of welding sequence on residual stress distribution in a multipass welded piping branch junction. International Journal of Pressure Vessels and Piping, 2012, vol. 95. *https://www.sciencedirect.com/science/article/pii/S0308016112000610?via%3Dihub*

[15] Wang J., Yuan H., Ma N., Murakawa H.: Recent research on welding distortion prediction in thin sheet fabrication by means of elastic FE computation. Marine Structures, 2016, vol. 47. *https://www.sciencedirect.com/science/article/pii/S0951833916000095?via%3Dihub*

[16] Hübner A., Teng J.G., Saal H.: Buckling behaviour of large steel cylinders with patterned welds. International Journal of Pressure Vessels and Piping, 2006, vol. 83. *https://www.sciencedirect.com/science/article/pii/S0308016105001298?via%3Dihub*

[17] Heinze C., Schwenk C., Rethmeier M.: The effect of tack welding on numerically calculated welding-induced distortion. Journal of Materials Processing Technology, 2012, vol. 212, no. 1. *https://www.sciencedirect.com/science/article/pii/S0924013611002755?via%3Dihub*

[18] Li Y., Wang K., Jin Y., Xu M., Lu H.: Prediction of welding deformation in stiffened structure by introducing thermo-mechanical interface element. Journal of Materials Processing Technology, 2015, vol. 216

https://www.sciencedirect.com/science/article/pii/S0924013614003793?via%3Dihub.
[19] Fricke W., Zacke S.: Application of welding simulation to block joints in shipbuilding and assessment of welding-induced residual stresses and distortions. International Journal of Naval Architecture and Ocean Engineering, 2014, vol. 6, 2014. https://www.sciencedirect.com/science/article/pii/S2092678216303144?via%3Dihub
[20] Barsoum Z., Bhatti A.A., Balawi S.: Computational Weld Mechanics – Towards a Simplified and Cost Effective Approach for Large Welded Structures. Procedia Engineering, 2015, vol. 114. https://www.sciencedirect.com/science/article/pii/S1877705815016793?via%3Dihub
[21] Fu G., Lourenço M.I., Duan M., Estefen S.F.: Influence of the welding sequence on residual stress and distortion of fillet welded structures. Marine Structures, 2016, vol. 46, 2016. https://www.sciencedirect.com/science/article/pii/S0951833915001021?via%3Dihub
[22] Zhou Q., Wang Y., Choi S-K, Cao L., Gao Z.: Robust optimization for reducing welding-induced angular distortion in fiber laser keyhole welding under process parameter uncertainty. Applied Thermal Engineering, 2018, vol. 129 https://www.sciencedirect.com/science/article/pii/S1359431117338371?via%3Dihub.
[23] Park J., An G.: Prediction of the welding distortion of large steel structure with mechanical restraint using equivalent load methods. International Journal of Naval Architecture and Ocean Engineering, 2017, vol. 9. https://www.sciencedirect.com/science/article/pii/S209267821630512X?via%3Dihub
[24] Wang H., Wang Z., Bai P., Hu S., Zhang Y., Wang R.: Optimized segmented heat source for the numerical simulation of welding-induced deformation in large structures. Advances in Engineering Software, 2018, vol. 117. https://www.sciencedirect.com/science/article/pii/S0965997817307354?via%3Dihub
[25] RFEM - Wielofunkcyjny, łatwy i intuicyjny, www.dlubal.com/pl/produkty/rfem/podstawowe-informacje (accessed on 21.01.2019)
[26] Giętka T., Ciechacki K., Chudziński M.: Kryteria wyboru technologii spawania zbiornika magazynowego. Inżynieria i Aparatura Chemiczna, 2012, no. 5.
[27] Kowalski D.: Wpływ imperfekcji wykonawczych na stan naprężeń w płaszczu stalowego zbiornika walcowego o osi pionowej. Politechnika Gdańska, Wydział Inżynierii Lądowej, Katedra Konstrukcji Metalowych, 2004. https://search.crossref.org/references
[28] PN-EN 1993-1-3:2008 Eurokod 3 - Projektowanie konstrukcji stalowych - Część 1-3: Reguły ogólne - Reguły uzupełniające dla konstrukcji z kształtowników i blach profilowanych na zimno
[29] Ziółko J.: Imperfekcje stalowych zbiorników walcowych, przyczyny ich powstawania, metody ograniczania. Materiały konferencyjne "Problemy Eksploatacyjne Baz Magazynowych Produktów Naftowych", Poznań, 11-12.05.1999.
[30] Myśliwiec M.: Spawalnictwo okrętowe. Wydawnictwo Morskie, Gdynia, 1966.
[31] Doerffer J.: Technologia budowy kadłubów okrętowych. Wydawnictwo Morskie, Gdynia, 1967.
[32] Analiza numeryczna MES spawania hybrydowego (HLAW) w aspekcie odkształceń spawalniczych łączonych elementów. Praca badawcza Instytutu Spawalnictwa, Gliwice, 2017.
[33] ASTM International, ASTM A131 / A131M - 14. Specification for Structural Steel for Ships.