Evaluation of Residual Stress In Specific Welded Nodes of River Ships

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Abstract. Rivers ships are complex welded structures, built of specific volume sections. Each volume section contains tens or hundreds of nodes, characterized by high restraint conditions. Due to the welding process, each node experiences local concentration of stresses. The paper aims to present a double, analytical and practical, evaluation of the residual stresses in a part of the double bottom deck. It has been built a physical model of such part of the double bottom deck and welding process was applied. The displacement was measured and the residual stress was obtained. It has been concluded that each new welding pass produced lower shrinkage than the previous one. A similar geometrical model was defined and simulated in FEM software. The results confirmed the results of the practical tests. It was, also, found that the cooling between the welding passes produced sudden variations of the displacements, all being in the sense of reducing the opening of the groove.

Keywords: stress · welding · ship's structure · inland ships

1 Introduction

With a majority opinion, one of the most important sectors of a country's economy is transportation. There are three main transportation options for the freight: road transportation, rail transportation and inland waterway transportation (IWT). For the last, the freight can be transported by inland vessels and barge convoys through inland waterways, channels and rivers between inland ports.

Transporting goods on inland waterways can be very advantageous, as barge convoys can transport more goods per distance unit (tones kilometer) than any other type of land transport. When moving large quantities of goods over long distances, the advantages of IWT comprise safety, sustainability, cost-efficiency, consumption of electricity per ton-kilometer, low accident rates and low congestions.

The overall quality and efficiency of the ship's manufacture has limited the rapid expansion of the shipping industry. Seawater corrosion in the vessels ballast tanks is a very serious problem and never too big to the importance given [1]. For example, the ship maintenance is always implemented to ensure that their main systems such

I. Dumitru et al. (Eds.): ICOME 2022, AHE 15, pp. 431–440, 2023.
https://doi.org/10.2991/978-94-6463-152-4_48

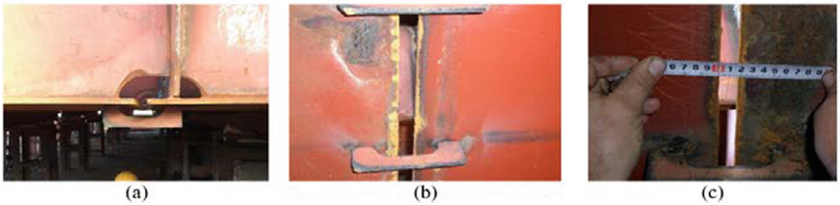

Fig. 1. Welding groove having incorrect large width along nodes

as propulsion, power, air conditioning etc. are fully operational. At the same time, the frequent occurrence of shipwreck catastrophes again requires the urgent need to improve the overall production of the ship quality [2].

Failures in the structure of ship could involve three types of damages: human life loss, damage of the shipped goods and ecological issues from minor to huge disasters related to the marine or coastal or inland rivers environment. Due to all of these issues, failures in the naval structures should be avoided and that starts with the fabrication and it ends with the exploitation.

One of the most used methods in ship and ship assemblies' fabrication is by welding process. This is a high productive and practical joining method comparing with others. But the welding of a ship's structure often led to local stress concentrations. Also, the heating and cooling affect both the material and the mechanical properties which introduce residual stress [3–5].

Unlikely other general welded ship's structures, the cargo ship's welded structures are more affected by the static load. The initial welding residual stress can be significantly reduced if this is taken into consideration when designing and building of a vessel and of welded structures. Very helpful can be the use of the flux-cored arc welding (FCAW) welding process, which can offer higher wire deposition rates. This process is highly productive and often used when fabricating welded ship structures [6].

A volumes section of a ship is composed of elements, stiffeners and nodes. A node is produced by two elements or by an element and its stiffeners or combination of the previous two situations (an example of a node is presented in Fig. 1(a) [7]. During the function of the ship, the force flows from one element to another by nodes. Same situation is met during welding processes, in which the force produced by the thermal cycle specific to welding is transferred from element to element by nodes.

The assembly of two volume sections of a vessel, at the level of the deck, but not only there, faces a problem related to the uniformity of the opening of the welding groove, and related to the maximum size of this opening [7]. There are many cases in which the opening of the root reaches 20 mm, while the welding technology specifies an opening in the range of 6–8 mm (with ceramic backing) (Fig. 1 (b)).

A welding groove with a larger opening means a larger amount of molten material introduced for filling, and subsequently higher expansions and contractions of the joint. Consequently, with the increase of the opening of the welding groove, an increasing of the permanent stresses and distortions of the welded joint are recorded. Figure 1(c) shows an example of an 18 mm groove width.

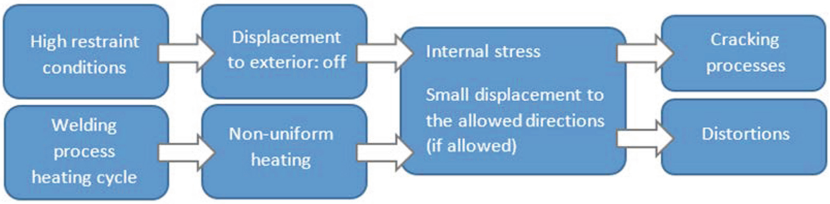

Fig. 2. Development of cracks and distortions during welding of a volume section

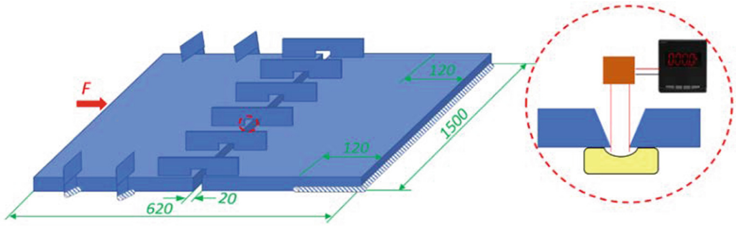

Fig. 3. Geometrical model used to build the physical model

The complete situation is presented in Fig. 2. The ending elements of a volume section are, generally, characterized by high restraint conditions, so displacements are limited allowed. Sometimes these displacements are even equal to zero. In such conditions, if apply the heating cycle of a welding process, which is a non-uniform heating in relation with the surface of the heated plate, internal stresses are developed, and specific distortions could occur. When the displacements are not allowed and the restraints are high, then cracking processes will be developed, immediately after the welding process or later by fatigue process [8]. Due to the high humidity that is specific to a shipyard the cracking process is accelerated [9–12].

A technological problem relates to the modification of the grooves during the welding, due to distortions, and that reduces the possibility to apply mechanization of the welding process, when weaving is used. Therefore, it is necessary to evaluate the change in the opening of the welding joint due to the applied thermal cycle. The coordinates of this study are presented below.

2 Experimental Study and Discussions

A physical model of the double bottom deck, with the dimensions of 1500 x 620 mm, was built (Fig. 3). On this model, the relationship between the value of a force applied perpendicular to the joint and the displacements of the joint flanks was first analyzed. For this, one of the components that form the joint was fixed by welding, and for the second one, only the possibility to move according to the direction of the force was constructively ensured. The force F was applied by using a specific hydraulic jack.

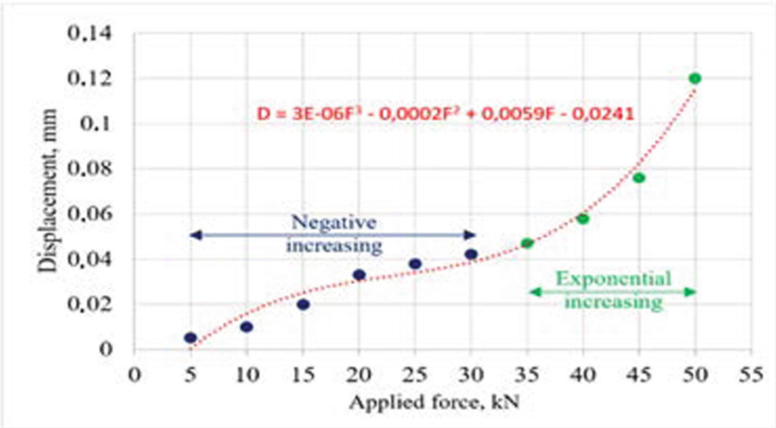

Fig. 4. The measured displacement when applied the external forces

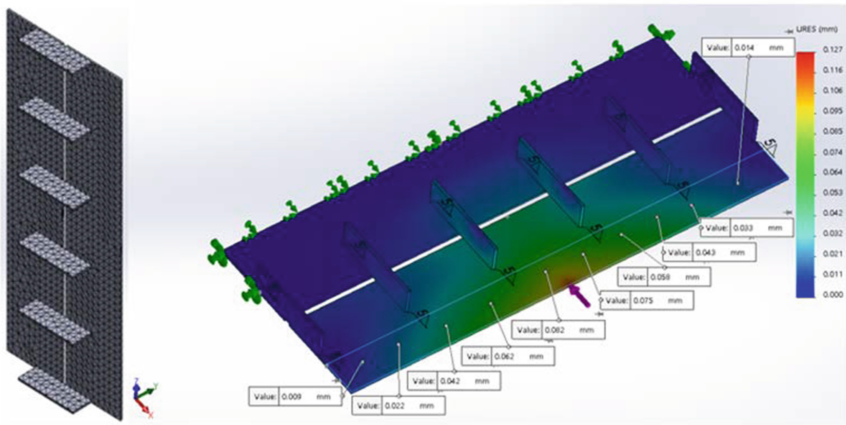

Fig. 5. Geometrical model subjected to simulation

Using a resistive sensor for distances, which was initially calibrated micro-metrically, the displacement values for various externally applied forces were measured. This created a comparison scale for future measurements performed during welding. The respective resistive transducer was connected to a voltmeter, the recorded voltage values being subsequently converted into mm of travel.

It has been obtained an almost linear evolution of the displacement in the middle of the groove, where the force was applied. A correct curve is polynomial with grade 3 one, but the coefficient of the third and the second-degree terms are below 10^{-4} (Fig. 4).

A simulation of the system above was done by using FEM (Fig. 5). Same geometrical model was subjected to different external forces (from 5 to 40 kN, step 10 kN).

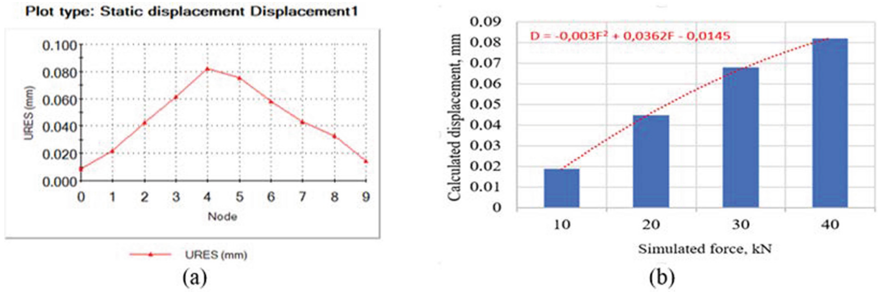

Fig. 6. Calculated values of displacements:(a) example for a 40 kN force and (b) maximum displacement values

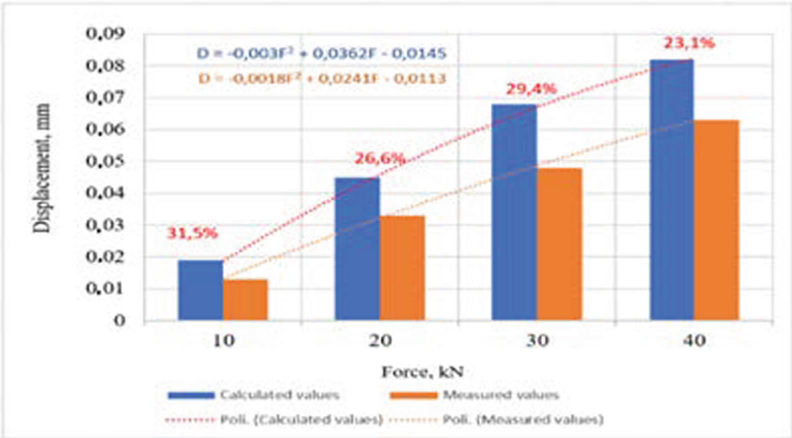

Fig. 7. Differences between calculated and measured values of the displacement

The simulation revealed also almost linear evolution of the maximum value of the displacements (Fig. 6), because the parabolic curve that follows the evolution has the coefficient of the second-degree at the 10^{-3} level.

The values obtained in the simulation process were compared with those obtained by applying force on the physical model, as shown in Fig. 7. Significant differences are found, around 30%, these being most likely due to the choice of the way of restricting the displacement of the geometric model (DOF = 0 on the opposite side of the force and on the sides, the length of the lateral simulated weld being 120 mm of the entire length of 300 mm).

The displacement values, measured in the previous experiment, became reference elements for the analysis of the evolution of the displacements of the groove's sides during welding. By measuring the proximity and distance of the two sides of the groove, it becomes possible to evaluate the forces developed by the applied welding process. For that, two identical physical models were subjected to welding, using two distinct welding technologies. The welding conditions were first chosen according to the approved

Table 1. Main coordinates of the welding process and the recorded values of the displacements for the two welded joints

Heat input, J/cm	See Fig. 8
Current, A	
Voltage, V	
Travel speed, cm/min	
9660	See Fig. 9
210	
23	
30	
14000	See Fig. 10
280	
25	
30	

welding procedure specification (WPS). Secondly, an increasing of the heat input was considered, in order to improve the productivity of the welding process, taking account of the high amount of molten metal which is necessary to fill the groove. All elements of the welding process and the applied welding parameters are presented in Table 1 and Fig. 8. The recorded values of the displacements are presented, as well. Using the first technology it was necessary to apply 5 welding passes, since for the second technology 4 passes were enough.

The recordings presented in Fig. 9 and 10 revealed, for each welding pass, 2 successive changes of the stress from positive to negative and back to positive, producing subsequently extension of the groove, narrowing and back extension. Welding the root layer, it is difficult to consider that the displacements describe a specific pattern.

Several successive transitions from positive to negative stress were met in the both cases. A clearer shape can be seen in the approved welding procedure, which has a trend line specific to the rest of the passes.

After the root pass, before starting the second pass and during the cooling from the breaks between the passes, an important narrowing of the groove was recorded. The recorded displacement during the break was: for the first procedure – from 0.04 mm to -0.12 mm; for the second procedure – from -0.01 mm to -0.22 mm. The increasing of the heat input produced larger shrinkage of the root pass and a displacement of 0.21 mm, which is 2.5 times of the shrinkage for the first heat input, was measured. Same collapse of the position happened during each break, when cooling produced contraction and shrinkage. Each new welding pass produced lower and lower shrinkage because the groove received new material inside and the shrinkage possibility was lower after each deposition.

Conditions:

Measurement: 1 measurement per 1 second

Welding: Process - FCAW / 136 according to ISO 4063, Wire - AWS A5.20: E71T-1 H4 EN 758: T 46 2 P C 1 H5, Gas – C1 according to ISO 14175:2008, Position – PA according to ISO 6947, manual mode, weaving, passes position according to figure 7 a (Approved WPS technology) and b (increased productivity procedure):

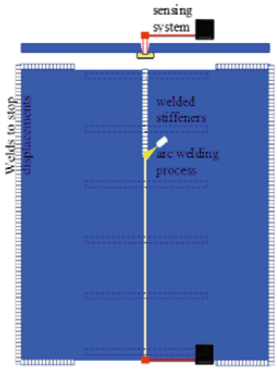

Fig. 8. Welding passes arrangement

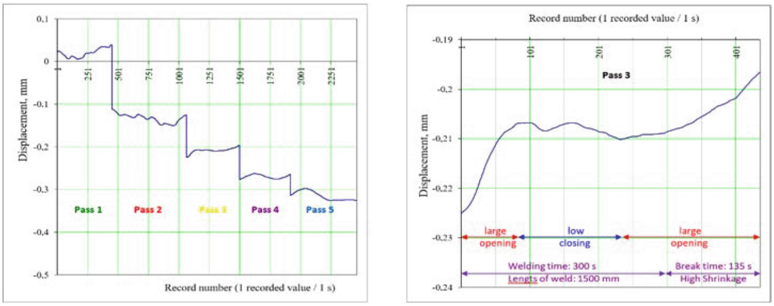

Fig. 9. Recording of the displacements for the approved WPS

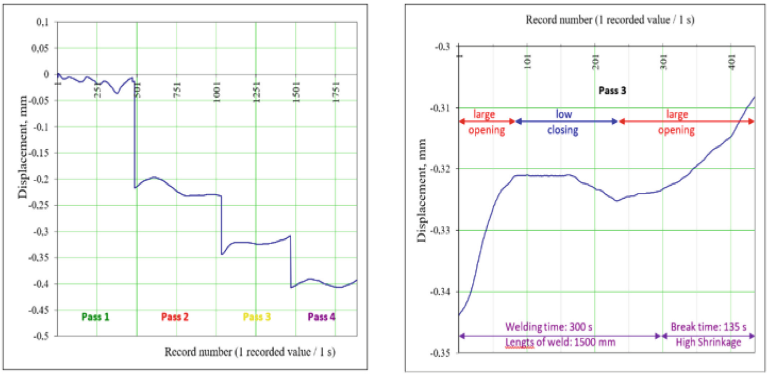

Fig. 10. Recording of the displacements for the approved WPS

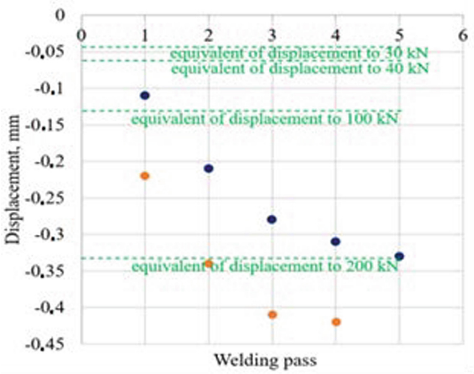

Fig. 11. The hypothetical force that could produce the measured displacements during welding

When started a new pass a relatively fast opening has been recorded for short time (about 1 min). A contraction starts after that for 2 min and a second modification, consisting in a new contraction along 2 min, will close the session for that pass.

The values recorded for the last welding pass is similar to the situation of cladding by welding, in which the produced stress is below yield stress [13–15]. Taking account of the values measured during the test with the applied mechanical force, and comparing the obtained values during the welding sessions with those values, it can be determined the forces developed inside the material during welding. Figure 11. shows the equivalence between the forces produced during welding and hypothetical forces that could produce similar effect if mechanically applied.

Taking into account that the evolution of the displacement during the application of external mechanical force is almost linear, the graph shows that during the welding forces of around 200–300 kN are developed. That is in line with results of previous research [7].

Already after the first welding pass, according to the second procedure, the forces produced in the welding material exceed values of 100 kN, approaching even 150 kN. After the second layer, the forces practically doubled in value. In the case of the approved welding procedure, the forces produced in the welding material are in the range of 100–200 kN for all welding passes applied after the root pass.

Regarding the stresses that were produced in the material, for the welding variant following the approved procedure the stresses increase until the immediate vicinity of the yield strength, taking into account that the material used was S235 steel (Fig. 12.). For welding, following the second procedure, the stresses doubled, the root pass producing around 460 N/mm2, which means plastic deformations of the material.

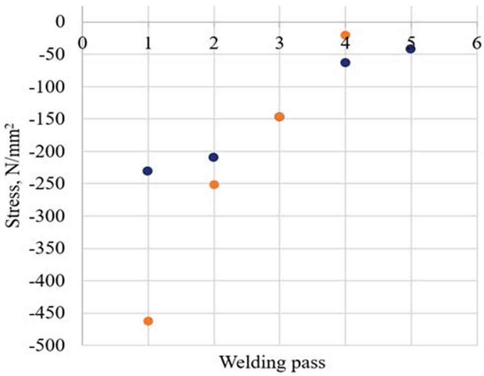

Fig. 12. The stress produced under the action of the thermal cycle

3 Conclusions

1. The analyzed structural element, containing several stiffening elements, supports relatively large forces. The application of an external mechanical force produced a displacement of the sides of the groove, reducing its width by a maximum of 0.12 mm for forces of approximately 50 kN. The maximum displacements can be used to build an empirical scale used as a reference for evaluating the displacement phenomena that occur during welding.
2. FCAW welding can be applied to weld on grooves having a 20 mm opening. The welding procedures can be more or less productive. The approved welding procedure provides 5 welding passes, but a procedure with only 4 welding passes was designed, so more productive. For each of the two procedures, a physical model with dimensions of 1500 x 620 mm was prepared. The welding was performed and the movements during welding were monitored using specific displacement sensors. It was found that the differences between the two welding procedures are relatively large. The 4-passes welding procedure produced approximately 20% more displacements, although the number of passes was smaller.
3. It was found that the cooling between the welding passes produced sudden variations of the displacements, all being in the sense of reducing the opening of the groove.
4. The evolution of the width of the groove has undergone two changes. At the beginning, the groove increased its opening for about 1 min out of the 5 min that the welding process lasted. For the next 2 min a contraction of the groove followed, and for the last 2 min it came back with an extension. Although, in terms of value, the expansion was wider than the contraction, however, due to the sudden variation during cooling, overall, the welding groove reduced its width by up to 0.4 mm, in the conditions of the existence of the 6 stiffening elements.
5. Due to the uniform heating under the welding cycle, stress is produced inside the material, and, for the approved procedure the stresses are increasing to a value around the yield strength, since for the higher heat input procedure the stress is double, exceeding the yield strength value.

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