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Prediction of welding residual distortions of large structures using a local/global approach

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Abstract

Prediction of welding residual distortions is more difficult than that of the microstructure and residual stresses. On the one hand, a fine mesh (often 3D) has to be used in the heat affected zone for the sake of the sharp variations of thermal, metallurgical and mechanical fields in this region. On the other hand, the whole structure is required to be meshed for the calculation of residual distortions. But for large structures, a 3D mesh is inconceivable caused by the costs of the calculation. Numerous methods have been developed to reduce the size of models. A local/global approach has been proposed to determine the welding residual distortions of large structures. The plastic strains and the microstructure due to welding are supposed can be determined from a local 3D model which concerns only the weld and its vicinity. They are projected as initial strains into a global 3D model which consists of the whole structure and obviously much less fine in the welded zone than the local model. The residual distortions are then calculated using a simple elastic analysis, which makes this method particularly effective in an industrial context. The aim of this article is to present the principle of the local/global approach then show the capacity of this method in an industrial context and finally study the definition of the local model.

Keywords: Welding; Residual distortions; Local/global approach

1. Introduction

In order to analyse the large structures widely used in the domains of aeronautics, automobile and shipbuilding, many multiscales methods have been developed from the years 1960s. These methods consist in dividing the global analysis into several levels to decrease the cost of calculation or overcome the limitation of the memory. When this procedure is limited to two levels and applied to the analysis of finite element in the industrial context, it can be called "local/global approach" or "global/local approach". The premier concentrates on the global level analysis, which makes it very suitable for the analysis of welding residual distortions.

Souloumiac et al. [1] developed a local/global solution to determine the residual distortions of the thin large structures. This method consists in simulating only one small part of the weld bead by a localised mesh and projecting the plastic strains to a global model of the complete structure as initial strains. The residual distortions can then be determined by an elastic analysis. This method is rather precise and makes it possible to model any kind of welds such as the T weld, the multipass, etc. It is certainly one of the most promising methods; however, certain points remain to be improved: this me-

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thod does not take account of the strain evolution on the global model nor of the reaction of the whole structure to the welds. Robin et al. [2] used this approach in a welding fracture analysis.

A decoupled plastic strain method 3D/3D was developed by L. Zhang et al. [3]. This method consists in performing a full thermo-elasto-plastic analysis on a local 3D model and subsequently projecting the six components of plastic strain from the middle part (stationary zone) of the local model to a global model in solid elements uniformly. The welding residual distortions are determined by an elastic analysis. However, the interactions among the parts and the structure constraints are neglected; the evolution of the strain in the course of time on the global model is not taken into account. It is assumed that all of the welds are applied simultaneously and so the welding sequence is not considered.

Andersen [4] used a local/global approach to simulate the residual distortions of a ship part induced by welding by combining the advantages of the dynamic mesh and the substructures. A complete calculation is performed on a local model corresponding to a weld situated in the global model which is composed of shell substructures, and then the nodal positions in the centre plane of the local model are used to update the displacements in the global model. The initial status of the local model representing the next weld is determined from the deformed global structure after the previous weld. The residual distortions can be calculated once all of the welds are integrated in the global structure. Some special 1D elements are employed to respect the compatibility between the 3D et shell elements. It is noticed that neither the strain evolution during the processing is taken into account nor the residual stress field is presented in the global model. Lastly, the complexity of implementation of this method is perhaps the most significant obstacle for its application.

In this article, the principle of the local/global approach, developed by Souloumiac et al. [1], will be presented in the first part, as well as the industrial applications of this method for the determination of the residual distortions of large structures. The second part will be devoted to the study of the definition of the local model. A technique called "space transformation" is used over a simplified plate model for the 3D simulations to determine the reasonable dimension for the local model. The influence of the dimension of the local model and the boundary conditions to the calculated plastic strains is studied.

2. Principle

In order to determine the residual distortions of complex structures induced by welding and subsequently study the influence of the welding sequence, a local/global approach, based on two levels modelling and aimed at combining the results obtained from a local mode (first level) with a global simulation over the whole structure (second level), has been proposed [1].

The plastic strains and the metallurgical microstructure induced by welding are supposed to be localised in the vicinity of the weld. It is therefore possible to determine these plastic strains by employing a 3D local model, concerning only the weld and its vicinity. As regards the complete structure, the global distortion is considered due to the local plastic strains produced by welding and the global behaviour can be thought as elastic. The local plastic strains are then transferred, as initial strains, to a global 3D model concerning this time all the structure and being evidently less refined in the welded zone. Lastly, a simple elastic analysis is carried out to determine the residual distortions.

3. Capacity

3.1 Simulation of GM front-rail

The analysis of GM front-rail [5] is taken as an example to illustrate the capacity of this local/global approach. Fig. 1 shows the geometry of this structure. In this analysis, two types of local models are used to reflect the fact that plates and profiles forming the structure have different thicknesses (Bumper 3 mm, Beam and Bracket 2.5 mm). Therefore, T-joints connecting Bumper with Beam is represented by one model (local model A) and T-joints connecting Beam and Bracket by another one (local model B). Assignment of local models to individual joints is schematically depicted in Fig. 2.

All the meshes used for both local and global models are created with VISUAL MESH™. Local simulations of the welding process account for all physical phenomena described in [6] and they are performed in SYSWELD™. The global analysis is carried out with PAM ASSEMBLY™. As can be seen in Fig. 3, the final distortions of GM front-rail are

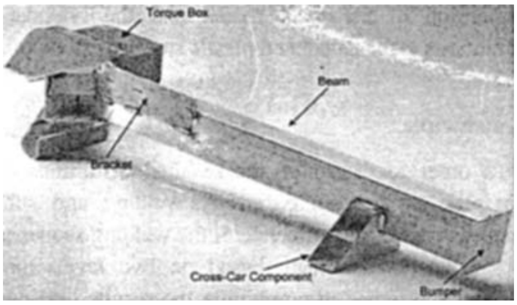


Fig. 1. Geometry of GM front-rail.

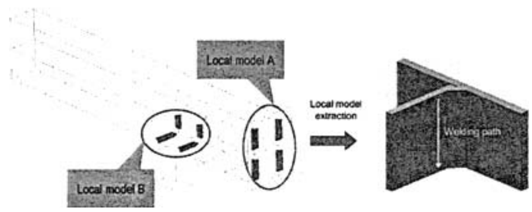


Fig. 2. Local model extraction.

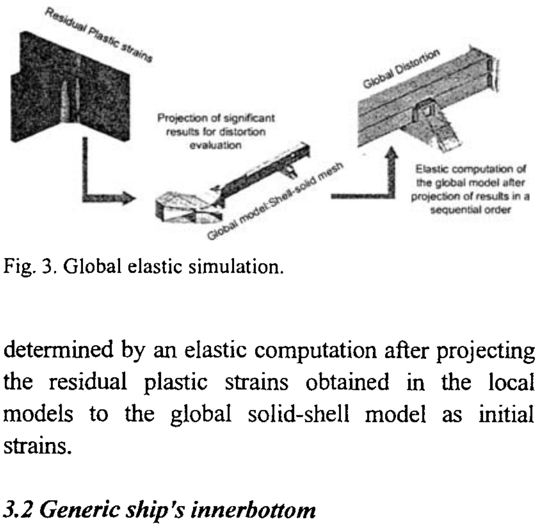


Fig. 3. Global elastic simulation.

determined by an elastic computation after projecting the residual plastic strains obtained in the local models to the global solid-shell model as initial strains.

3.2 Generic ship's innerbottom

Another example is from the seminar "ShipTech 2007" [7] concerning an analysis of a generic ship's innerbottom. A portion of a full-scale, generic innerbottom, whose size is set to 12.5×11.5×5 ft in order to get maximal measurable distortions, as shown in Fig. 4, is taken into account. The tank top is made of HSLA-100 (high strength low alloy steel) and its thickness is 1 inch. The longitudinal girders and transverse floors are made of HSLA-65 and its thickness is set to ½ inch. Flux core arc welding (FCAW) with AWS E71T-12M electrode is used for

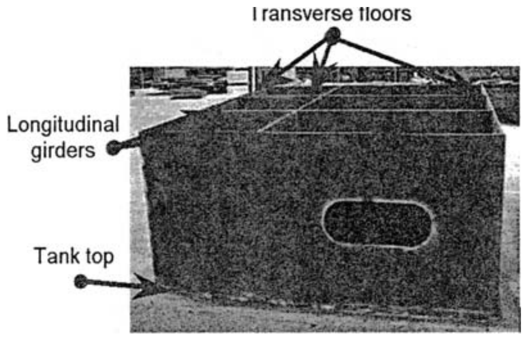


Fig. 4. Geometry of a portion of a generic ship's innerbottom.

the 72 moving fillet welds.

A designed welding sequence is used to induce significant distortions. This is not an optimal sequence for real-world welding considering that it is not intended to mimic shipyard construction practices. Exterior dimensions are measured by Optimal with a Comet T-SCAN™ handheld laser scanner in conjunction with an OPTOTRAK™ position tracker and interior dimensions are measured with a Stanley FatMax™ Tru-Laser™ distance measurer.

Three types of local models, as shown in Fig. 5, are required in this analysis. All the other welds can be represented by them and only their welding directions and their locations on the structure change. A transient 2D calculation with a moving heat source is used to model multipass welding processes. The heat source is adjusted by comparing to the macrograph of weld. To simulate correctly the local effects of the weld, a fine mesh is required for the sake of the sharp variations of thermal, metallurgical and mechanical fields in this region. The metallurgical transformation and non-linear material properties are taken into account.

The global mesh, discretized with 3D shell elements, is composed of about 60,000 nodes and 40,000 elements. The simulation accounts for the experimental welding sequence by modifying the stiffness of the assembly due to the deposit of each joint. The global simulation takes 1.6 hours on a dual core PC with 2 Gb RAM.

The final distorted shape of generic ship innerbottom is shown at 10× actual distortion in Fig. 6. The results of the simulations are compared with experimental measurements of distortions, as shown in Fig. 7. As we can see, the predicted distortion trends and magnitudes agree with the experimental results fairly well.

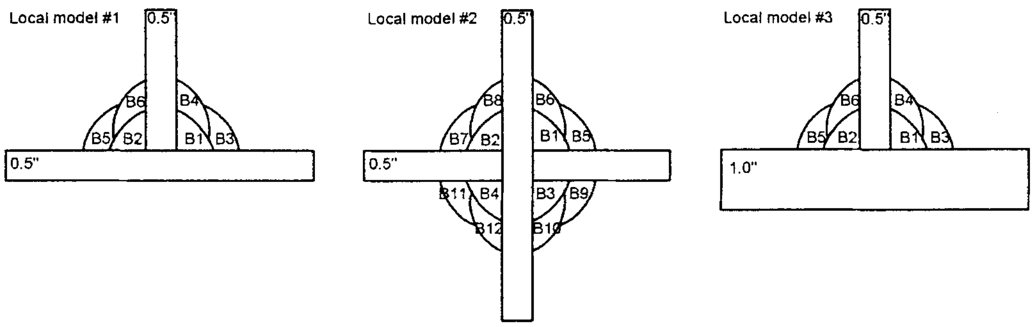


Fig. 5. Local models required for the global analysis.

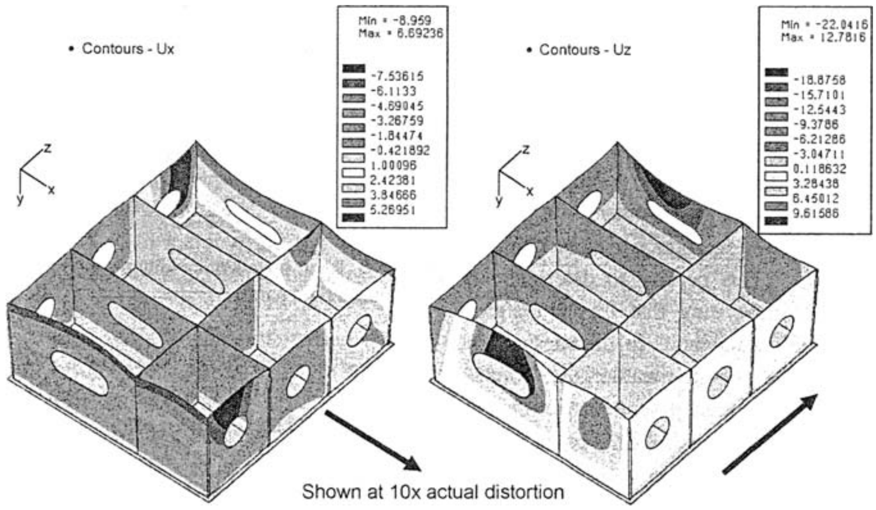
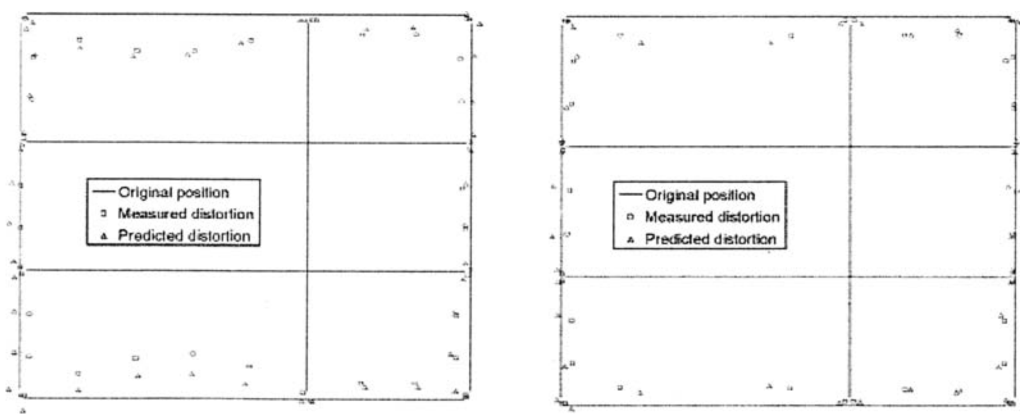


Fig. 6. Final distorted shape of generic ship innerbottom.



(a) top of structure (b) mid-height of structure

Fig. 7. Comparison to metrology.

4. Definition of the local model

The local simulation must reflect the welding conditions such as that exist in the whole structure, which demands to choose the boundary conditions adapted. The problems raised by this approach are about two points. It is concerned first of all to regain the correct temperature distribution in the incomplete model. Then, it is necessary to study the size of the local model and the boundary conditions applied to its frontier to reproduce correctly the mechanical conditions imposed by the rest of the structure, and as a consequence, evaluate correctly the plastic strains induced by welding.

4.1 Proposal

To determine the reasonable dimensions for the local model in the context of the thermal simulation, the 3D simple simulations are carried out on a simplified plate model extended laterally. The elements representing an infinite boundary condition in one direction are used to reproduce the heat diffusion far from the source. This permits to determine the dimensions which make sure that the temperature over the frontier is homogenous in thickness. Once this size decided, the thermo-metallurgical coupled calculations on a local model extended with thermal shell elements are performed. The choice of the optimal dimensions depends then on the mechanical aspect.

Concerning the mechanical aspect, the influence of the local model dimensions and the boundary conditions applied to the frontier on the calculated plastic strains must at this moment be studied in comparison with a referential calculation.

4.2 Calculation of a reference

In regards to the calculation of the referential model, a welding simulation of the thin large structure is carried out (Fig. 8). Considering the symmetry of the welding processing of this structure, only half of the structure is modelled. A heat source moves in the centre of the upper face to deposit a 140 mm long weld. The structure is made of 16MND5 (French norm; A508, American norm) steel because of its well known characteristics [8].

The calculations have been performed with the commercial finite element code SYSWELD™ [9] with the small displacements hypothesis. It is noticed

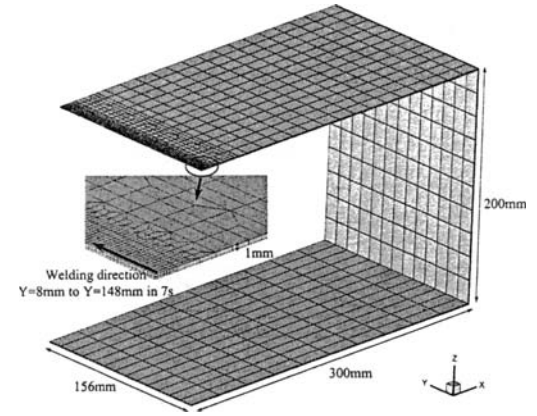


Fig. 8. Structure used as a reference model.

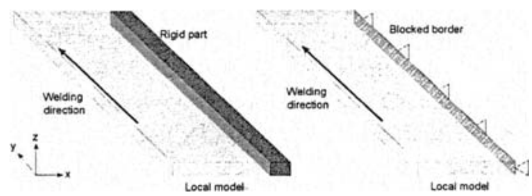


Fig. 9. Rigid boundary conditions applied to the frontier by adding a rigid part.

that the equivalent plastic strains exist only in the vicinity of the weld and the size of the zone affected by these strains is about 4 mm.

4.3 Minimum width of local model

The technique "space transformation" has been introduced in SYSWELD™ [9] to deal with the problems with open boundaries. For our little penetrating heat source, the temperature distributions are almost homogenous in thickness 5 mm away from the welding line, it's therefore reasonable to choose this value for the minimum width of the local mesh which will be used in the mechanical simulation.

4.4 Optimal dimension of local model

The local models extended with the shell elements are used in the coupled thermo-metallurgical calculations by taking into account the minimum width defined previously. Thus the width of the 3D part is taken greater or equal to 5 mm. The heat source applied and the material are the same that used in the previous case. The model concerning the mechanical calculation is only composed of 3D elements and one 4 mm wide part, is chosen to perform the comparison

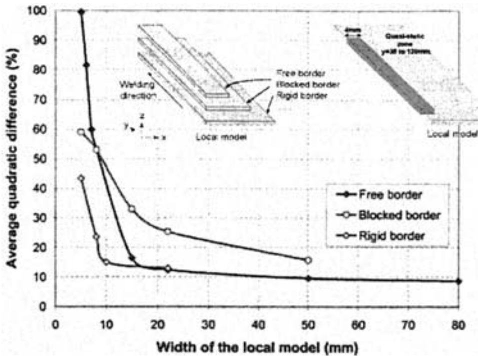


Fig. 10. Average quadratic difference in function of the lateral dimension of the local model.

with the referential model.

In order to consider the effect of the rest of the structure on the formation of the plastic strains, two types of boundary conditions are proposed (Fig. 9). The first one consists in using a very rigid part added to the frontier of the local model to keep the boundary in plane, and it is convenient to vary the value of Young's modulus so as to increase the rigidity. The second one uses a border blocked in the transverse direction.

The average quadratic difference of plastic strains compared to the results of reference, in function of the lateral dimension of the local model, is illustrated in Fig. 10. Concerning the calculations with boundary conditions "blocked border", it is noticed that they give better results than those with "free border" only when the width is inferior to about 8 mm. As can be seen, regarding the results with boundary conditions "free border" or "rigid border", the average quadratic difference of plastic strains becomes almost insensible to the width of the local model once it is superior to 15 mm in this case. Furthermore, the calculations with boundary conditions "free border" give acceptable results since the average difference is around 10 %. When the width is inferior to 15 mm, the calculations with "rigid border" reduce the difference greatly. However, the average difference with "rigid border" is up to 40 % for the case of the width of the local model being 5 mm, which is still unacceptable. Even though, the boundary conditions "rigid border" permit to obtain a large reduction of the average quadratic difference of plastic strains compared to the results of reference. The results can be improved by increasing the value of Young's modulus of the rigid part, or by enlarging the lateral dimension of the local model.

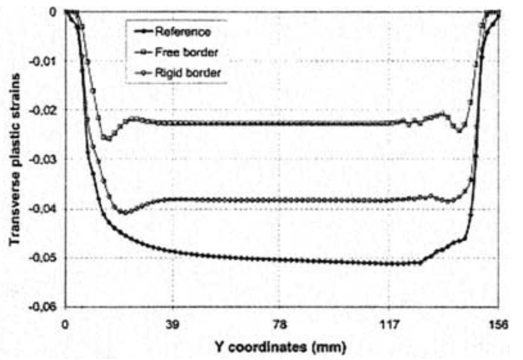


Fig. 11. Comparison of transverse plastic strains (x=0 mm).

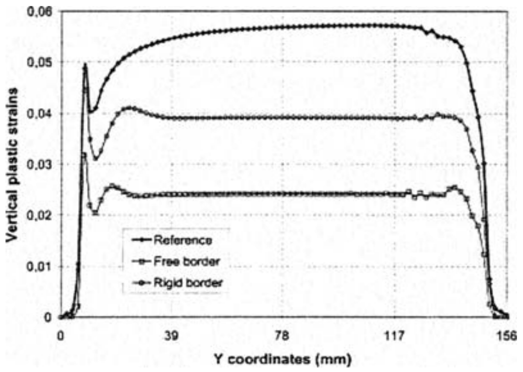


Fig. 12. Comparison of vertical plastic strains (x=0 mm).

The plastic strains are also compared to those obtained by the referential simulation. The comparison of the transverse plastic strains obtained by a local model of 5 mm, over the line x=0 mm, is shown in Fig. 11 and the comparison of vertical plastic strains is represented in Fig. 12. The result of longitudinal plastic strains is not presented here considering that the magnitude of these values is not significant. It is noticed that the simulations with "rigid border" can give a considerable reduction of plastic strains difference in comparison with the results with "free border".

5. Conclusions

The determination of welding residual distortions of large structures is difficult. The local/global approach presented in this article seems to be a very promising method, particularly for the optimisation of welding sequence in an industrial context.

In order to reflect the real welding conditions, the boundary conditions applied to the frontier of local model is studied. The boundary condition "rigid border" permits to decrease the plastic strains difference considerably.

In fact, the minimal dimensions of the local model depend also on the heat source and on the thickness of the structure; the influence of these two parameters will be taken into account in further work.

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All the simulations are performed with the softwares VISUAL MESH™, SYSWELD™ and PAM ASSEMBLY™ developed by ESI-GROUP.

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